

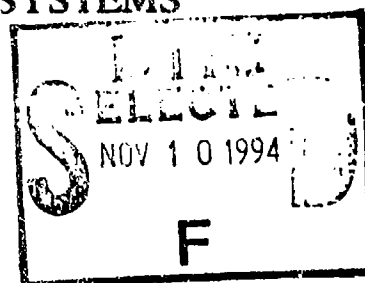
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IDAPAPER P-2852

WORLDWIDE RADIONAVIGATION SYSTEMS



H. M. Federhen

September 1993

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PREFACE

This report, funded as an IDA Central Research Project, is a collection of technical descriptions of worldwide radionavigation systems written by the author over a period of several years. The sections on Loran and Omega were written about 5 years ago in connection with a study of battlefield navigation, and the section on the Global Positioning System (GPS) was written about 2 years ago as part of a study of weapons guidance. The discussion of the history of navigation and the section on Transit were written for this paper.

The purpose of the report is to provide a single, reliable source of information on the characteristics and performance of the major radionavigation systems now in use, and to help in evaluating their utility in various civilian and military applications.

The author wishes to thank Dr. David L. Randall for his encouragement and for providing the funds for the project. The review committee, Mr. Harold A. Cheilek, Mr. Philip J. Walsh, Dr. Robert D. Turner, and Dr. C. Leslie Golliday, provided many valuable comments and suggestions which improved the coverage and coherence of the paper. Without these people the report would have been much less than it is. The author would also like to thank Mr. Jules McNeff of the Office of the Assistant Secretary of Defense for Command, Control and Communications [OASD(C3I)] for his inputs in the course of the review.

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EXECUTIVE SUMMARY

The accuracy and/or performance of navigation techniques has improved steadily since the early days of the cross staff and star sightings, and the current set of worldwide radionavigation systems has continued that trend. Loran-C, which became operational about 1960, has a location accuracy of 0.1-0.25 nautical miles (nmi), but its range is limited to 1,000-2,000 nmi. Omega, which became operational about 1980, is less accurate (2-4 nmi) but provides true worldwide coverage. Transit, the first satellite navigation system, became operational in 1964. It gives worldwide coverage with two-dimensional positioning accuracy of 25 meters (m) but is limited to a minimum interval between fixes of 30 minutes or more. GPS, which is now becoming fully operational, provides full-time worldwide coverage with three-dimensional accuracies of 25m (position) and 0.1 m/s (velocity).

The performance characteristics of these systems are compared in the following Table ES-1.

Table ES-1. Comparison of Worldwide Radionavigation Systems

System	Accuracy	Coverage		Measured Value		Fix Dimensions
		Worldwide	Continuous	Position	Velocity	
Loran - C	185-460m	No	Yes	Yes	No	2D
Omega	3.7-7.4km	Yes	Yes	Yes	No	2D
Transit	25m	Yes	No	Yes	No	2D
GPS	Horiz 21m Vert 29m	Yes	Yes	Yes	Yes	3D

The technical details of these systems are discussed in great detail in the text, and the reasons for their performance characteristics are thoroughly explained. For now, a few comments will help to understand the entries in the table:

- The values shown in the second column are Predictable Accuracies: the accuracy with which a user can locate himself with respect to a known coordinate system such as Lat/Long or Universal Transverse Mercator (UTM). Other modes of operation have accuracies which are considerably better: for example Relative Accuracy (the accuracy with which two users can locate themselves with respect to each other) and Differential Accuracy (location with

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respect to a known, surveyed reference point). In fact, both Transit and the Global Positioning System (GPS) have differential accuracies of 1 meter or better.

- Loran provides almost complete coverage of North America, Europe, and the Middle East, as well as the air and ship lanes across both the North Atlantic and North Pacific. However, there is no coverage of most of Asia or of the southern hemisphere.
- Transit is limited by its design parameters to only one satellite in view at a time. Therefore, there is a minimum time between fixes of 30 minutes, and continuous operation is not possible.

Based on its technical performances, GPS is clearly the best system. It can also be shown, however, that GPS is probably the most vulnerable to interference or jamming.

The single weakness of GPS is that it is quite vulnerable to noise, interference, and jamming. An analysis of the jammer power required to deny the use of the systems gives the following results:

To jam GPS from a range of 50 km

Carrier loop: 6W

Code loop: 80W

To jam Transit from a range of 50 km: 50W

To jam Loran-C from a range of 200 miles

Loran station at 200 miles: 5 MV²

Loran station at 500 miles: 200 kW

To jam Omega (worldwide): 1.5 kW to 150 MW

Despite this one potential weakness, GPS is an extremely sophisticated navigation system with outstanding performance characteristics. It will serve the needs of millions of users for many years to come.

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Moving from one known point to another known point is called navigation. Moving from one unknown point to another unknown point is called being lost.

I. INTRODUCTION AND BACKGROUND

Over the past few centuries, the pace and scope of both international commerce and warfare have increased dramatically, and the demands placed on the navigation techniques needed to support them have increased correspondingly. When commerce was by caravan or sailing ship, the pace was slow, and navigation by landmarks or celestial observations was more than adequate. Warfare tended to be a prolonged operation with more time spent in moving and preparing for battle than in actual combat. Napoleon could tell his commanders to "march toward the sound of the cannon" and be reasonably sure that they would arrive at the right place on the battlefield in time to influence the outcome of the battle.

Today, commerce is truly global, with travel times measured in hours rather than weeks, and warfare is increasingly conducted by small, independent, highly mobile tactical units or by long-range missiles rather than by massed armies. There is an urgent need for real-time, highly accurate navigation systems that will serve users anywhere in the world.

This paper will discuss and compare the four global radionavigation systems now in use: Loran, Omega, Transit, and the Global Positioning System (GPS).¹ Chapters II through V will give separate technical descriptions of each of the systems, and Chapter VI will compare their performance and antijam capabilities.

The paper is limited to worldwide (strategic) systems and will not cover the short-range (tactical) systems such as VOR, ILS, or MLS, which are used by civilian aircraft, and JTIDS or PLRS, which are used by the military.

¹ GLONASS, the satellite navigation system developed by the Soviets, is very similar to GPS and will be described together with GPS in Chapter V.

A. DEFINITIONS

The various aspects of the navigation process are commonly defined as follows:

- **Position Finding.** Determining one's location with respect to an established coordinate system such as latitude and longitude (Lat/Long) or Universal Transverse Mercator (UTM). Altitude may also be required.
- **Guidance (or Pilotage).** Determining the correct course to steer by using external reference points and without necessarily knowing one's own position. Examples would be the use of landmarks or radio beacons or, in the case of aircraft, an Instrument Landing System (ILS).
- **Navigation.** The entire process of directing the movement of a vehicle from one point to another. It includes trip planning, course selection, position monitoring, and course correction.
- **Dead Reckoning.** Determining the position of a vehicle based on the distance traveled from a previous position. It involves the measurement of speed, direction, and time.

It should be noted that the errors in dead reckoning are cumulative and, unless corrected from time to time by a position-finding fix, can become intolerably large.

These functions are clearly interrelated. Speed and direction can be determined from a series of position fixes, navigation can be accomplished by steering toward a series of landmarks or radio beacons, and position can be found by measurements made on two or more beacons or landmarks.

Loran, Omega, and Transit are position-finding systems,² while GPS allows the simultaneous measurement of both position and velocity. In all cases, however, velocity (speed and direction) can be determined by making a series of position fixes over a period of time and interpolating (differentiating).

B. A BRIEF HISTORY OF NAVIGATION TECHNIQUES

The first navigator was probably the primitive hunter who used landmarks to find the direction back to his village and measured distance by counting paces or estimating elapsed time. A more formal approach, involving astronomical observations of the sun,

² In theory, velocity could be determined by measuring the Doppler shift of the Loran or Omega carrier. However, the carrier frequencies are so low that the Doppler shift is exceedingly small and difficult to measure (see discussion on page 112).

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moon, and stars evolved over time. The cardinal points of the compass were established, and the barrows and henges of England and France, which date back to 8000 BC, were aligned in a north-south direction. The Babylonians (1800 BC) and the Egyptians (1500 BC) observed the sun, divided the horizon into 360°, and measured the length of the year as 365-366 days. By perhaps 500 BC, sufficient long-term data had been gathered to establish that the length of the year was 365.2422 days and that the synodic cycle of the moon (the period between full moons) was 29.531 days.

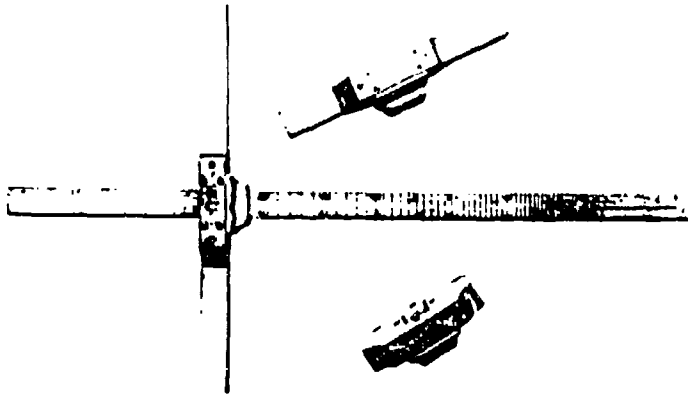
The pole star was used as a guide star as early as 1000 BC,³ and it was known that it circled the actual pole and introduced an error in the measurement of true north (as much as 3.5° in the 15th century). It was also known that certain "guide stars" in Ursa Minor could be used to determine when the pole star was "in rule" (i.e., at the latitude of the pole) and to make appropriate corrections at other times.

Progress in the art and science of navigation can perhaps be best tracked by examining its components individually:

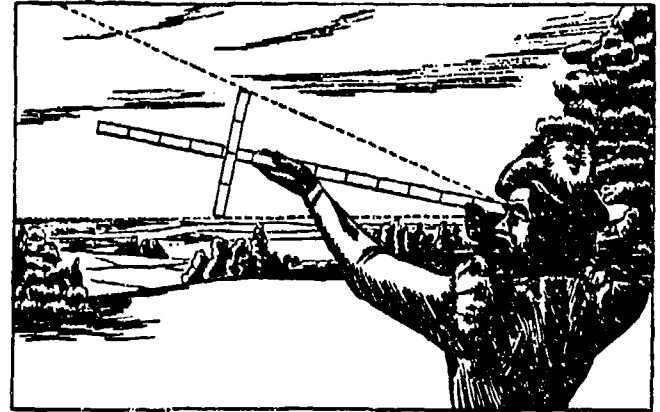
- **Latitude.** The concept of latitude (the distance north or south from the equator) was known in 200 BC by the Alexandrians and was probably discovered by noting the changes in the elevation of stars while sailing on a north-south river (e.g., the Nile). Near the equator or in the Southern Hemisphere, the pole star is not visible and the elevation of the noonday sun can be used to measure latitude. Early instruments for measuring celestial elevation includes the quadrant or the astrolabe, which used a vertical reference, and the cross staff, which used the horizon as a reference (see Figure 1). A modern sextant can measure elevation to about 10 seconds of arc and thus determine the north-south position of the observer to within a few hundred meters.
- **Longitude.** From about 200 BC, the early navigators knew that the earth was spherical and understood the concept of longitude (the distance east or west from some reference point). Several ingenious (and inaccurate) methods were developed to determine longitude: measurement of the angle of the pointer stars of the Big Dipper, observation of the eclipses of Jupiter's moons,

³ The earth's spin axis is tilted with respect to the plane of its orbit by about 23°, and it precesses like any other gyroscope, making a complete cycle in 25,753 years. As a result, the axis traces out a circle in the sky, and the apparent pole star changes over time. In 3,000 BC the pole star was α Draconis, the brightest star in the constellation Draco (the Dragon), located about halfway between the bowl of the Little Dipper (Ursa Minor) and the middle star in the handle of the Big Dipper (Ursa Major). The pole star is now Polaris, the bright star at the end of the handle of Ursa Minor, and in 7400 AD it will be the brightest star in the constellation Cepheus. In 100 BC, navigators probably used α Draconis even though it was about 24° from the pole of the earth's axis of rotation.

or measurements of "lunar distances" (the angles from the moon to selected stars). None of these techniques worked any better than merely estimating the east-west distance traveled by dead reckoning.



(a)



(b)

The navigator would hold one end of the staff beside his eye, move the cross piece until one end aligned with the horizon and the other with the pole star (or sun), and then read the altitude from a scale on the staff.

Sources: (a) Reference I-1, (b) Reference I-2

Figure 1. The Cross Staff

Longitude can also be determined by measuring the elevation of a star from two different positions, one of which is at a known location (for example, the ship's home port). The mathematical solution, which involved spherical trigonometry, was found by the Flemish astronomer Frisius in 1530. However, the two measurements had to be made simultaneously [a timing error of 1 minute causes a position error of 15 nautical miles (nmi) for a vessel at the equator], and no clocks with sufficient accuracy were available until 1760. The first tables, which permitted easy use of such measurements by mariners, were published in the Greenwich Nautical Almanac of 1767.

- **Time.** Time is reckoned by the passage of the sun and stars across the heavens, and the early division into 24 equal hours was done in Christian and Moslem countries to establish the proper time for prayers. The earliest time-measuring instruments were sun dials, standard calibrated candles, and water clocks (which date from 1500 BC in Egypt, Greece, and China). The astrolabe, which was in use before 600 AD, is a portable analog computer that

calculates the local solar time from a measurement of the peak sun elevation (noon) or peak star elevation (meridian transit). By 1600 AD, the most complex astrolabes (see Figure 2) included even a correction for the eccentricity of the earth's orbit around the sun.



Source: Reference I-9

Figure 2. The Astrolabe (1548 A.D.)

Sand glasses, which were introduced to shipboard use in the 9th or 10th century, allowed time to be measured even when the sky was overcast. They were turned regularly at half-hour intervals, and the day was divided into "watches" based on these events.

Mechanical clocks were invented in Europe in the late 1200s and were at first used only to control the bells in churches or public buildings. A visible hour hand was added in the mid-1300s. The minute hand was not added until the late-1600s when the pendulum and anchor escapement was invented and provided sufficient accuracy to warrant such a refinement.

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In 1714, the British parliament offered a prize of £ 20,000 to anyone who could find a method of determining longitude to within 30 miles during a sea voyage. It was awarded to John Harrison for a chronometer, which was successfully tested in 1761-62. This remarkable device kept time to within 1 part in 10^5 (an error less than 1 second per day) on a pitching, rolling ship.

The chronometer has been supplemented by radio broadcasts of time signals (1923), radio nav aids such as Loran (1943) and, more recently, by satellites. The standard reference for time is now maintained by atomic clocks, and worldwide synchronization can be kept to an accuracy of a few nanoseconds.

- **Azimuth.** Early mariners determined their ship's heading by measuring the azimuth to Polaris. This was not possible when the weather was overcast and was also impossible at or below the equator because there is no pole star in the Southern Hemisphere. The compass, using a needle magnetized by a lodestone, was in use by 1100 AD. Permanently magnetized needles were not introduced until about 1700 AD. The magnetic variation (the angle between magnetic north and true north) was identified in 1580. Since the geographic and magnetic poles are separated by a fixed (or at least slowly varying) distance, the magnetic variation is a function of longitude which can be calculated and published to aid mariners in correcting their magnetic compass readings. The inverse procedure was also used for a while: the magnetic variation was measured by observing the compass and the pole star, and this value was used to obtain a crude estimate of longitude.
- **Speed, Depth, and Other Navigation Aids.** The distance traveled by a ship in a day or in a sandglass interval was originally estimated by the captain, based on his knowledge of the speed of his ship under various conditions of wind, loading, sail configuration, and sea state. The first device for measuring speed was the "Dutchman's Log." A piece of wood was thrown off the bow of the ship and the navigator measured the time it took to reach the stern. Knowing the length of the ship, the speed could then be calculated. By 1550, the "log" had been attached to a rope and knots in the rope were counted as it unwound from a reel. The number of knots in a measured time interval gave the ship's speed. In 1688, the "patent log," a towed rotor with stabilizing vanes, was introduced in England.

Depth was measured by using a weighted line thrown over the side of the ship. The original unit of measure was the Norse "Fathmr," or "outstretched arms," which has been standardized to the 6-foot fathom. The weight also carried a cup or was coated with pitch to pick up sea bottom samples, from which an indication of position could be found.

Other aids included observations of the color of the water, the types of waves, the appearance of birds, and many known landmarks. The distance to a cliff

could be measured by timing the echoes of shouts, drumbeats, or even cannon shots.

Navigation was by dead reckoning, based on estimates of speed, time, and azimuth. The estimates could be no better than the measurement techniques, and these were subject to large and unexpected errors. In addition, the velocity of the water currents, and the sideslip of the ship under sail (the "leeway") increased the errors of the dead reckoning estimates.

C. EARLY NAVIGATION

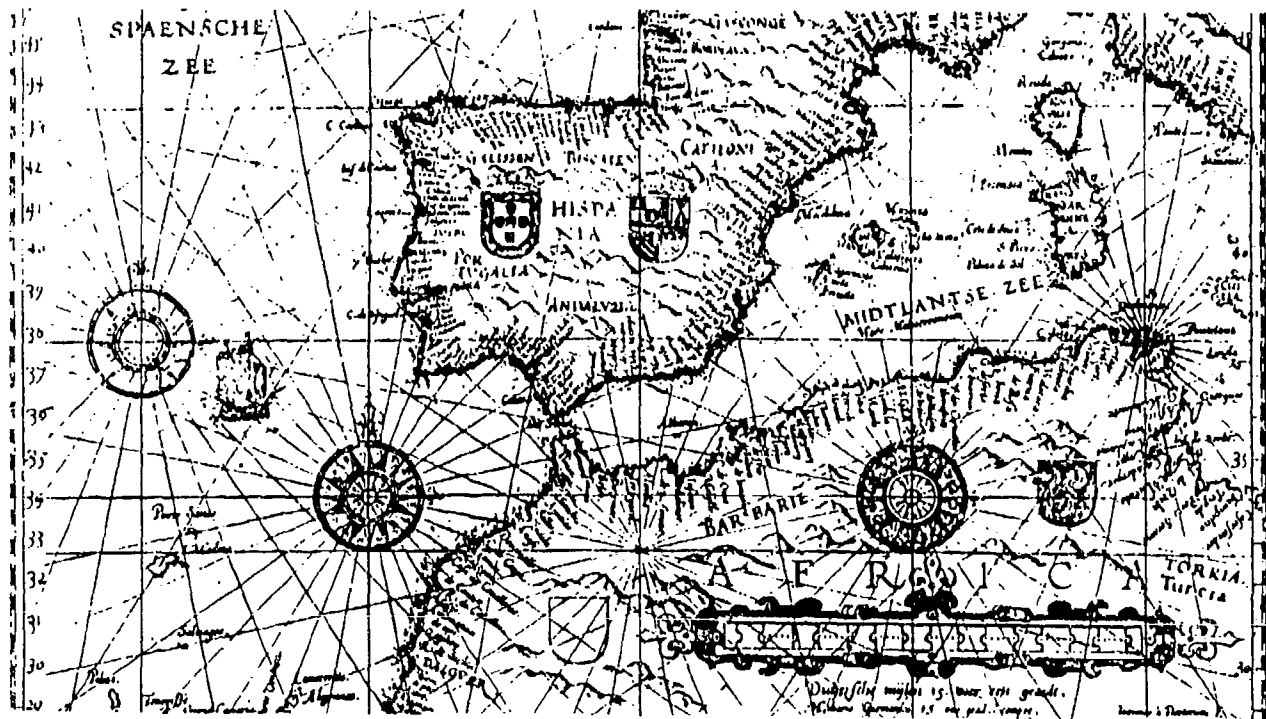
Egyptian wall paintings dating back to 3500 BC show reed boats, equipped with sails, transporting both people and cargo. These early trips were made on rivers and along shorelines, generally during daylight and within sight of land. Navigation was by following a series of known landmarks. However, voyages out of sight of land were not long in coming. By 2500 BC there was regular trade between Egypt and the island of Crete, a distance of about 300 miles, and by 1500 BC there were trade routes over most of the Mediterranean. The Phoenicians were importing tin from Cornwall by 600 BC, about the same time that the Vikings settled Iceland and visited North America, and by 100 AD Egyptian and Greek ships were sailing to India directly across the Indian Ocean. By 1519, enough was known that Magellan could leave on his voyage to circumnavigate the globe. Bowditch (Reference I-1) says that his navigational equipment included "sea charts, a Terrestrial globe, wooden and metal theodolites, wooden and wood-and-bronze quadrants,⁴ compasses, magnetic needles, hour glasses and 'timepieces,' and a log to be towed astern." Note that he could measure speed, direction, and latitude, but not longitude.

Navigational aids were developed to support the longer sea voyages. The earliest known lighthouses were built before 660 BC, and the lighthouse known as the Pharos of Alexandria⁵ (one of the seven wonders of the ancient world) was built about 280 BC. The first written aids to navigation were pilot books, which date from at least 400 BC. They listed the courses to be sailed between ports and contained data on winds, currents, headlands, sea bottom conditions, port entrances, and anchorages. The first navigational maps, called portolans (see Figure 3), appeared in the 13th century AD. They showed

⁴ A forerunner of the modern sextant, used for measuring the altitude of the sun or stars.

⁵ The Pharos was reported to be more than 135 meters high and was lit by a fire which burned at night. It was still standing in the 12th century AD.

excellent detail of the features along the Mediterranean shoreline and included both a scale of miles and several sets of rhumb lines (lines of constant bearing) centered on wind roses at various points on the chart. To determine a course, the navigator would draw a line from his departure point to his destination, find the rhumb line most nearly parallel to it, and track it back to the parent wind rose to find the proper sailing direction. Distance was measured by using dividers and the scale of miles, and the duration of the journey was estimated from the predicted speed of the ship. Navigation consisted of setting the course by observing the pole star or, when it became available, by the magnetic compass. The portolan charts made no reference to latitude and longitude and ignored the fact that the earth is a sphere and that allowance must be made for the fact that the meridians of longitude converge toward the poles. They also allowed no corrections for magnetic variation (the angular difference between magnetic north and true north). However, within the relatively confined area of the Mediterranean, where navigation consisted of going a certain distance along a certain rhumb line, the charts were satisfactory for their purpose.



Source: Reference I-3

Figure 3. An Early Portolan Chart

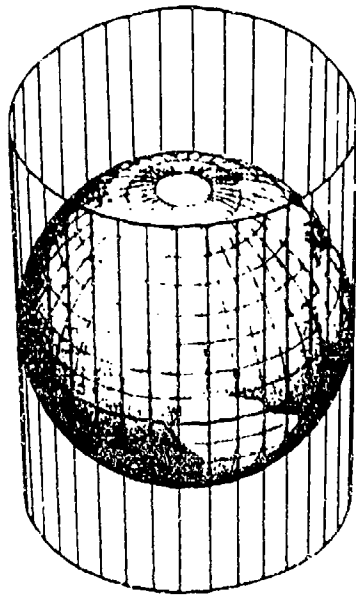
As voyages became longer, and particularly as they sailed north along the coast of Europe and south along the coast of Africa, the "flat earth" Portolans were no longer satisfactory. Rhumb lines were no longer straight, and sailing by bearing and distance alone was not adequate. In 1418, Prince Henry the Navigator established a navigation academy at Sagres, Portugal, to devise solutions to the problem and to train navigators in their use.⁶ In addition to producing maps and charts of ever-increasing accuracy, the academy developed the technique of "parallel sailing" or "constant latitude sailing." Here the navigator would sail due north or south (using the pole star as his guide) until he reached the latitude of his destination, and then sail east or west at constant latitude (using the elevation of the pole star as his guide) until he reached his destination. The method was clearly inefficient in terms of both time and distance but, without any reliable way of measuring longitude, it was one of the only means available.

The addition of the magnetic compass and the marine chronometer gave the navigator the last of the tools needed for global navigation. One final development which should be mentioned came in 1569 when Gerardus Mercator published his world map on a "true projection suitable for navigation." The Mercator projection is a projection of the spherical earth onto a cylindrical surface, as shown in Figure 4a.⁷ In this projection, the spacing between the meridians of longitude is expanded (distorted) as one moves from the equator to the poles. The defining feature of the Mercator projection is that the meridians of longitude and the parallels of latitude are expanded at the same ratio (equal to the secant of the latitude with a small correction for the ellipticity of the earth). As a result, angles are preserved, and map features retain their true shapes, although there will be distortion of their relative sizes as a function of latitude. More important from the navigator's point of view is that lines of constant bearing (rhumb lines) appear as straight lines on a Mercator projection.

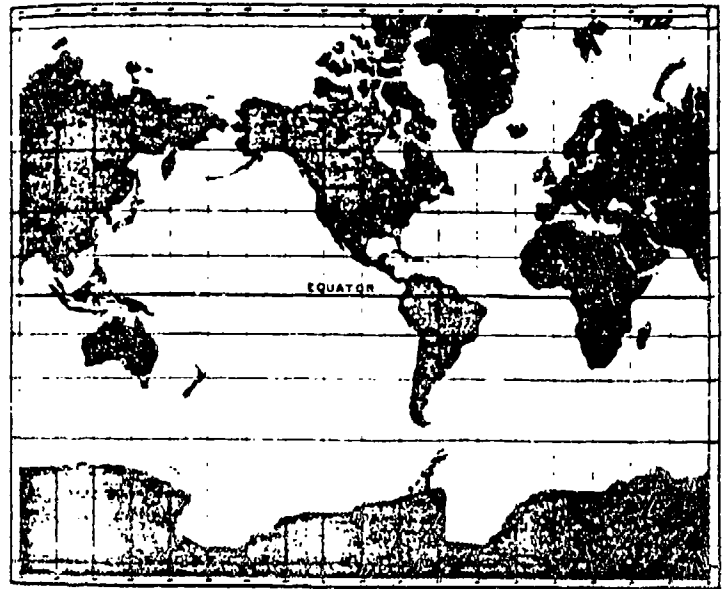
⁶ The cross-staff may have been invented here.

⁷ The circle of tangency in Figure 4a is the equator, and this is an *equatorial cylindrical orthomorphic* (shape-preserving) projection. If one of the meridians of longitude were the tangent circle, it would be a *transverse* projection; and if some other great circle were used, it would be an *oblique* projection.

CHART PROJECTIONS



(a)



(b)

Source: Reference I-1

**Figure 4. Cylindrical Projection
and a Mercator Map of the World**

D. THE GYROCOMPASS

The development of the magnetic compass revolutionized navigation by making it possible to determine azimuth even on overcast days when the sun and stars were not visible. There are, however, certain inherent errors which limit its effectiveness. The first is the variance between true north and magnetic north, which has been discussed earlier. This is a known quantity, and the proper correction can be found by reference to tables in a nautical almanac. The second results from the fact that the compass will respond to any extraneous magnetic material or magnetic field in its vicinity. The fields from current-carrying wires, the steel hull of the ship, the cargo, carelessly placed tools, or even the contents of a sailor's pockets can cause a deviation of the compass. Many ingenious techniques have been developed to correct these deviations.⁸ Two soft iron balls, one on either side of the compass, serve to provide the basic compensation for the hull of the ship. Then soft iron rods placed in tubes around the compass and small permanent magnets

⁸ For a truly exhaustive treatment of the subject, see Bowditch (Reference I-1), Section 621ff and Chapter VII.

under the compass card are adjusted to remove the last of the deviation. Unfortunately, the deviation changes every time a large metal object (e.g., a gun turret or a lifeboat davit) moves, every time the cargo is changed, and even as the ship rolls, and the corrections must be made again.

The gyrocompass, which was developed independently by H. Anschutz (Germany) in 1908, E. A. Sperry (United States) in 1911, and S. G. Brown (England) in 1916, overcomes these problems. When properly set up, a gyrocompass will automatically point to true north and is unaffected by its surroundings.

The basis of the gyrocompass is the gyroscope, which was invented about 1810 as a children's toy and which found its first serious application in 1852 when Leon Foucault used one to demonstrate the rotation of the earth. The device consists simply of a rotating mass on an axle, usually mounted in a set of gimbals so that the spin axis is free to turn in any direction. It has two inherent properties which are critical to the operation of the gyrocompass:

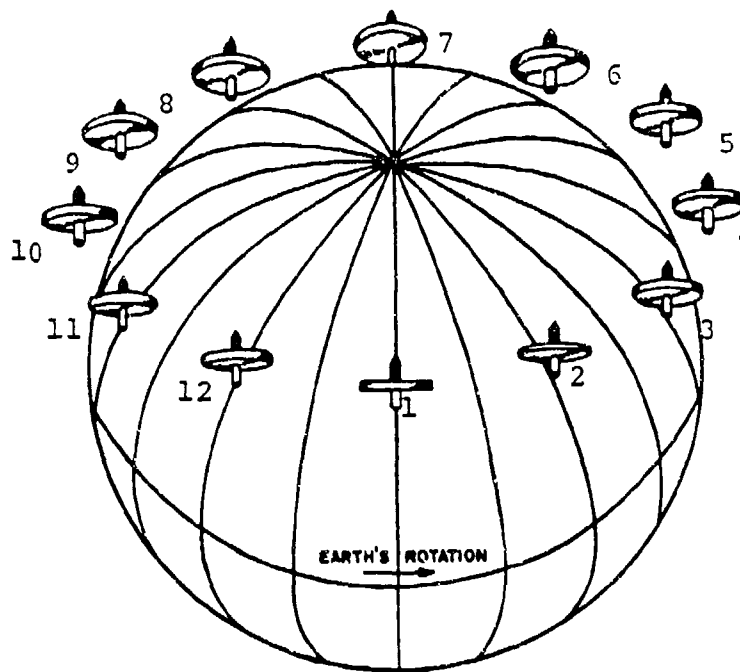
- **Gyroscopic Inertia or Rigidity in Space.**⁹ In the absence of friction or other external forces, the spin axis of the gyroscope will maintain its direction in inertial space, regardless of the motion of the platform on which it is mounted. Thus if the spin axis is pointed at a star, it will continue to point at the star even as the earth rotates and the apparent position of the star changes. This is shown in Figure 5.

A gyroscope at position 1 is oriented horizontally and with its spin axis pointing north. As the earth rotates, an observer will see the spin axis move to the east and upward between positions 1 and 7, and to the west and downward from position 7 back to position 1. During a complete day, the tip of the spin axis will appear to trace out a circle around the pole star.

- **Precession.** If a torque is applied, that tends to change the direction of the spin axis, the resultant motion is not in the direction of the torque, but rather in a direction at right angles to both the torque and the spin axis. This motion is called precession¹⁰ and is familiar to anyone who has watched a toy gyroscope standing on the floor or on a pedestal: The force of gravity acts vertically on the gyroscope but, instead of tipping over, it moves in a horizontal circle.

⁹ This property is a direct result of the conservation of angular momentum.

¹⁰ If S , T , and P are unit vectors in the direction of the spin, torque, and precession (defined according to the standard right-hand rule), they will obey the vector cross product $P = S \times T$.



Source: Reference I-1

**Figure 5. Apparent Movement
of the Spin Axis of a Gyroscope**

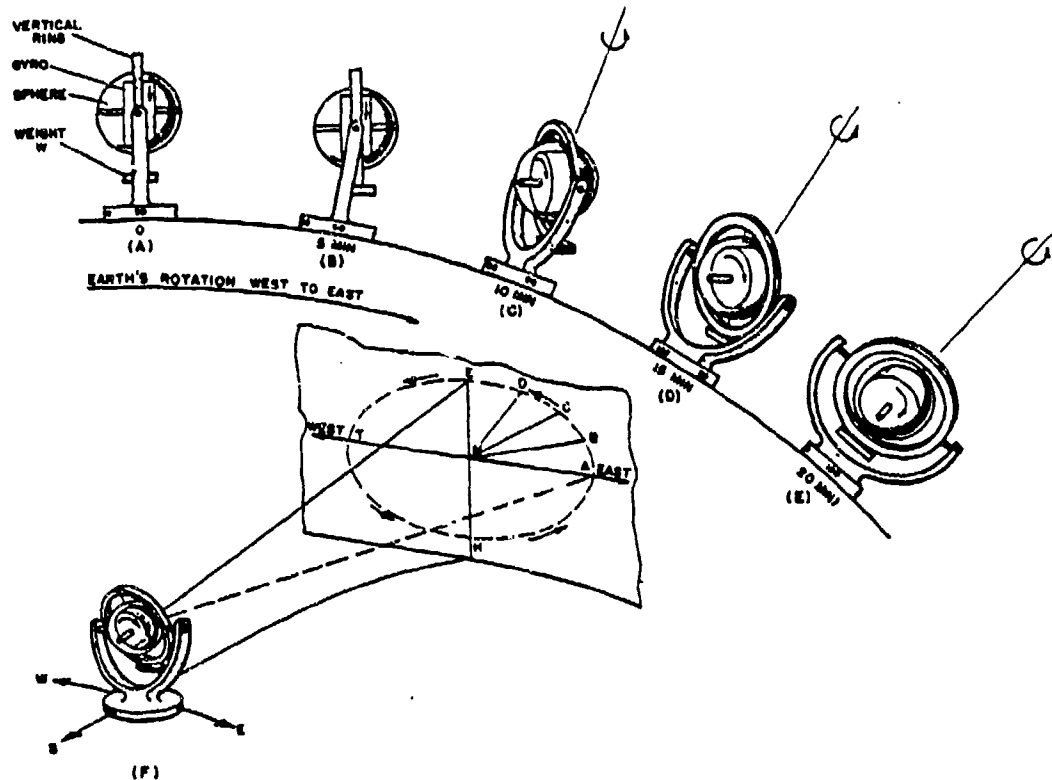
The gyroscope is useful because it tends to maintain its orientation in inertial space. To convert it to a gyrocompass, it must be made to automatically seek and maintain true north. This is accomplished by adding a so-called pendulous weight to the bottom of the rotor ring as shown in Figure 6.

As the gyroscope moves with the earth's rotation, the spin axis tends to tilt upward, the pendulous weight acts to rotate it back to horizontal, and the resulting precession rotates it toward the direction of true north. The tip of the spin axis will trace out an ellipse, centered on true north, and with a period of 84.4 minutes.¹¹ If no other forces act on the device, it will continue to trace out these ellipses indefinitely. However, when damping is added,¹² the trace of the spin axis will spiral inward and the device will become stable in

¹¹ The device behaves as a Schuler pendulum, which acts as if it had a length equal to the radius of the earth and has a period of 84.4 minutes.

¹² This may be done by adding a second weight at the side of the gimbal ring, by immersing the gimbal mounts in a viscous fluid, or by providing damping through an external feedback circuit. All three techniques have been used (see Reference I-1).

the only position in which no torques are acting upon the spin axis: with the axis horizontal and aligned with the axis of the earth (i.e., pointing to true north).



Source: Reference I-1

Figure 6. Effect of Pendulous Weight and Earth's Rotation on Gyroscope

The above discussion assumed that the gyrocompass was stationary on the earth's surface and that the west-to-east motion of the earth's surface was the only component of the velocity. If the velocity of the platform has a north or south component, then the resultant velocity (earth plus platform) will have a north or south component. Since the gyrocompass will settle into a position at right angles to the resultant velocity, this introduces an error, to the west if the platform is moving north and to the east if it is moving south. The error clearly depends on the latitude and the platform velocity and is easily corrected, either manually or automatically, once these values are known.

The gyrocompass is an ideal heading reference since it automatically seeks true north and is unaffected by its surroundings. Its only drawback when compared to a magnetic compass is that it requires a reliable source of power to keep the gyroscope spinning.

E. INERTIAL NAVIGATION

Inertial navigation is a logical extension of the principles behind the gyrocompass and is favored in many applications because it is passive and requires no external references of any kind. It is, in effect, a highly sophisticated dead reckoning system and is widely used in ships, submarines, aircraft, and guided missiles.

The heart of the inertial navigation is a high-precision gyroscope mounted on three-degree-of-freedom gimbals. This establishes an "inertial platform" (also called a stable platform), which maintains its orientation in inertial space, independent of the motion of the vehicle on which it is mounted. A set of three orthogonally oriented (mutually perpendicular) accelerometers is mounted on the inertial platform. The combination of the inertial platform and accelerometers is often called an Inertial Measurement Unit (IMU) and provides all of the data needed for navigation: Rotations of the vehicle around any of the three spin axes (roll, pitch, and yaw) are measured by direct comparison with the stable platform, and the outputs of the accelerometers are integrated once to find the velocities and a second time to find distance along each of the three coordinate axes (for example east-west, north-south, and up-down).¹³ When properly initialized, the inertial navigator is the ultimate self-contained dead reckoning system.

There are, of course, complications. The first is that the system operates in four separate coordinate systems:

- **Inertial Reference Frame.** Three orthogonal axes that neither accelerate nor rotate with respect to inertial space (i.e., with respect to the fixed stars). It is the reference system for the inertial platform.
- **Earth Frame.** The earth frame has its origin at the earth's center and its z-axis pointing north along the earth's spin axis. The x and y axes are in the equatorial plane, usually referenced to the Greenwich meridian.
- **Navigation Frame.** This frame is centered on the IMU of the vehicle being navigated. The x-y plane is tangent to the surface of the earth, with the x-axis pointing true north, the y-axis pointing east, and the z-axis pointing vertically down. It is often referred to as an NED frame.
- **Body Frame.** The origin of the body frame is at the center of mass of the vehicle. Typically, the x-axis points forward, the y-axis to the right, and the z-axis downward toward the bottom of the vehicle (not necessarily vertical). These are the roll, pitch, and yaw axes of the vehicle.

¹³ For a more detailed description, see References I-1 or I-5 (under the heading Navigation, Inertial).

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Since IMU measurements are made in the inertial frame, navigation is done in the earth frame or the navigation frame, and steering commands and responses are in the body frame, the navigation computer must continually make conversions among all four frames. This represents the largest load on the computer and has been made possible only by the advent of high-speed digital processors.

The second major problem arises from the fact that the direction of the local vertical (the direction of the force of gravity) changes with respect to the inertial platform as the earth rotates or the vehicle moves. This is because the inertial platform remains stationary in inertial space, while the local vertical always points to the center of the earth. When this happens, the force of gravity acts on all three accelerometers instead of only the vertical one and, since an accelerometer cannot distinguish between gravity and other external forces, false readings will result which can be corrected only with great difficulty. These can be avoided by applying external torquing forces to the inertial platforms so as to keep it always aligned with the local horizontal plane. When this is done, only the vertical accelerometer sees the force of gravity and, since it is a known quantity, it can be subtracted out.

Other, generally uncorrectable, errors are caused by gravitational anomalies, bearing friction, gyro bias, and gyro drift. These result in drift error rates of 0.1 to 1.0 degree per hour, depending on the quality of the IMU. A typical commercial unit has a drift rate of 0.25 degree per hour which, at typical jet aircraft speeds, results in a navigation error of 1 to 2 nmi per hour. As with all dead reckoning systems, the errors are cumulative so, for example, a trans-Atlantic flight will accumulate an error of 5 to 10 nmi. This is more than adequate for en route navigation but not for landing or for most military applications.

F. RADIONAVIGATION SYSTEMS

Modern radionavigation systems, starting with Loran in 1940 and continuing through the yet-to-be-completed Global Positioning System (GPS), have added a new dimension to the science of navigation. The gyrocompass and inertial platforms provided a basis for dead reckoning systems which were subject to long-term drift and uncontrolled errors. Radionavigation systems, on the other hand, are position-finding systems which provide an accurate measure of a user's location at some instant of time. The four most common radionavigation systems will be described in detail in the balance of this paper.

The dead-reckoning and position-finding systems complement each other remarkably well, since the former provides short-term stability and the latter provides

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periodic updates to maintain system accuracy. The most sophisticated modern navigation systems include three basic components:

- An inertial platform, which provides a stable reference for the measurement of vehicle orientation and velocity.
- A position-measuring system such as Loran or GPS, which can be used to correct the long-term drift of the inertial platform.
- A navigation computer, which takes those inputs, along with any others that may be available (e.g., speed indicator, altimeter, etc.) and determines the position and velocity of the vehicle. Kalman filtering is usually used in order to ensure an optimum solution.

Using these techniques, it is now possible to keep track of the position of a vehicle to an accuracy of a few meters and to know its velocity to an accuracy of 0.01 meters per second.

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II. LORAN

A. HISTORY

During the early years of World War II, Great Britain and the United States both recognized the need for long-range, accurate radio navigation systems to support air raids over Europe and operations in the waters around the British Isles. As a result, the British developed the Gee system for use by high-altitude long-range aircraft, and the Americans developed Loran (Long-Range Navigation), primarily for use by surface ships and low flying aircraft over the ocean and the channel. Although the design goals of the two systems led to some technical differences [Gee operated on several frequencies from 20 to 85 megahertz (MHz) with a pulse width of 6 microseconds (μ s), and Loran operated at 1.95 MHz with a pulse width of 45 μ s], they were remarkably similar: Both were high-power, pulsed, hyperbolic, grid-laying long-range navigation systems. Also, both used manual data readout: The operator would see pulses from two stations displayed on a cathode ray tube (CRT), would adjust time delay circuits to superimpose the envelopes of the two pulses, and would then read the time delay and use it to calculate his position.¹ Readout accuracy was about one percent of the pulse width, and the lower bound of system accuracy was about 100 yards for Gee and 200 yards for Loran.

The first technical proposal for what would become Standard Loran-A (Loran-A) was made in the fall of 1940, and the development program was turned over to a newly formed group at the Massachusetts Institute of Technology (MIT) Radiation Laboratory in the spring of 1941. Wartime priorities led to an extremely accelerated schedule: the first two experimental stations went on the air at Montauk Point, Long Island, and Fenwick Island, DE, in January 1942, using 100 kilowatt (kW) transmitters. The Loran chain was completed in October 1942 with stations at Baccaro and Denig, Nova Scotia. It was turned over to the Coast Guard in January 1943 and was declared fully operational in December 1943. Deployment continued rapidly. The Alaskan chain became operational in July 1944, and by February 1945 there were active chains in Hawaii, the Marshall Islands, the China-Burma-India theater, and Pacific coverage was being extended by stations on

¹ This will be discussed in more detail later.

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Iwo Jima, Okinawa, and Guam. Coverage of Canada, Greenland, Norway, and Great Britain was also provided. By the end of the war in 1945, 70 Loran-A stations were providing navigation coverage over an area of more than 60 million square miles, or almost one-third of the earth's surface.

Standard Loran (Loran-A) operates at a carrier frequency of 1.95 MHz with a pulse repetition rate of 25 pulses per second (pps), a pulse width of 45 μ s, and a radio frequency (RF) bandwidth of about 100 kilohertz (kHz). These parameters give a reliable daytime range of about 700 nmi over sea water. At night, due to higher noise levels, the range is reduced to about 500 nmi. Over land, the ground wave is attenuated by absorption into the earth's surface, and the reliable range is only about 100 miles.

Increased range can be realized at night by using the "skywave"--the signal reflected from ionosphere. Accuracy is reduced because of uncertainties in the height of this ionized layer, but skywave coverage of all of Central Europe from Spain and France to Poland and Rumania was realized with an accuracy of 1-2 nmi using Loran stations in Scotland, Algeria, Tunisia, and Libya.

These values are summarized in Table 1.

Table 1. Reliable Range of Loran A (nautical miles)

Time	Ground Wave		Skywave
	Land	Sea Water	
Day	100	700	
Night		500	1,400

Early in the Loran program, it was recognized that longer range, especially over land, could be realized by moving to the low-frequency (LF) band (30-300 kHz). The MIT Radiation Laboratory developed such a system (called, logically enough, Low-Frequency Loran), operating at a frequency of 180 kHz, with an RF bandwidth of 8-10 kHz, and a pulse width of 300 μ s. Testing started in the spring of 1945 with stations at Key Largo, FL; Cape Fear, NC; and Brewster, MA. Each station had 90 kW of peak pulse power, and the antennas were 1,300-foot wires suspended from barrage balloons. Although ranges of 700 miles over land and 1,200 miles over sea water were demonstrated, the system was not successful because of skywave interference. At ranges beyond a few hundred miles, the

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ground wave and skywave were both received, and the peak of the resultant pulse envelope could be shifted by as much as 50 μ s (an error of 8 nmi). Two solutions were proposed:

- Increase the RF bandwidth and reduce the pulse width so that the ground wave and skywave could be separated on the operator's oscilloscope
- Use cycle-matching--i.e., match cycles of the RF carrier (which are 5.5 μ s long) rather than matching pulse envelopes (which are 300 μ s long).

Further developments continued after the war but at a much slower pace. The frequency band from 90 to 100 kHz was established by international agreement for long-range navigation systems, and Sperry was put on contract to build a system at this frequency. It was called Cytac² and was tested successfully from 1953 to 1955. Using transmitters with about 500 kW peak pulse power, and antennas consisting of either 625-foot or 1,200-foot top-loaded vertical towers, ground wave ranges of 1,800 miles were demonstrated. The cycle-matching technique described above was also developed and tested successfully.

Finally, in 1957 the Navy developed an official requirement for a long-range, high-accuracy radio navigation system. Equipment from the Cytac program was used, minor modifications were made to the waveform, and the system was renamed Loran-C. Stations were established at Jupiter Inlet, FL, Carolina Beach, NC, and Martha's Vineyard, MA, and system tests were started in 1958.

The carrier frequency of Loran-C is 100 kHz, and the RF bandwidth is 20 kHz. Details of the pulse shape, pulse width, and pulse repetition frequency will be presented later. Loran-D, the transportable version of Loran-C, has almost identical parameters. This also will be discussed later.

² An acronym for Cycle-matching Tactical bombing system.

B. LORAN CONCEPT ³

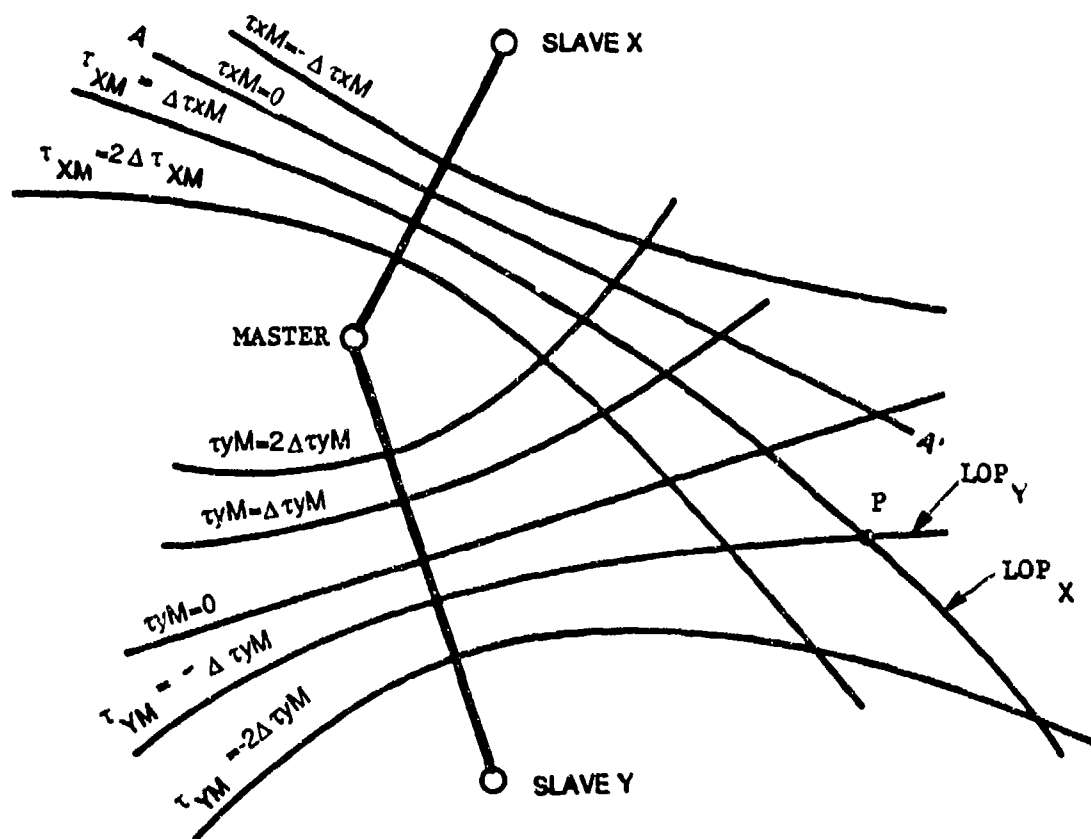
Hyperbolic radio aids to navigation operate on the principle that the difference of time of arrival of signals from two stations, observed at a point in the coverage area, is a measure of the difference in distance from the point of observation to each of the stations.⁴ The locus of all points having the same observed difference in distance to a pair of stations is a hyperbola⁵ and is called a Line of Position (LOP). The intersection of two or more LOPs defines the position of the observer. To understand this concept, refer to Figure 7.

Suppose that the Master Station and Slave X transmitted pulses simultaneously (time difference $\tau_{XM}=0$) and that a user received the pulses at the same time. He would then know that he was located somewhere on the perpendicular bisector of the baseline between the Master and Slave X--on the line labeled AA' in the figure. If, on the other hand, he received the signal from the Master before the signal from Slave X by some small time difference, $\Delta\tau_{XM}$, he would be located on another Line of Position (LOP), shown as LOP_X in the figure. A similar measurement using the Master and Slave Y would yield another Line of Position (LOP_Y), and the intersection of these two lines determines the position of the user.

³ Some of the material in this section is taken from MITRE Technical Reports MTR-6270 and MTR-6449 (References II-1 and II-4), with the permission of the authors.

⁴ This is strictly true only if the propagation parameters are equal along the paths from the two Loran stations to the receiver. At the surface of the earth, however, the wave propagation speed is reduced by several factors: First, electromagnetic waves travel slightly slower in the atmosphere than in free space. Second, the speed is a function of the surface over which the wave is moving (lower over water than over land, for example). It depends on the salinity of the water and the conductivity of the land and is affected by buried iron deposits and even the roughness of the terrain. The necessary corrections are called *primary and secondary phase factors* and have been extensively studied, both theoretically and by calibration of actual Loran grids. Data and procedures for applying the phase factors are widely available (see, for example, Reference II-5).

⁵ The complete locus is a three-dimensional hyperboloid of revolution, which intersects a two-dimensional plane in a hyperbola. The complete three-dimensional navigation solution is the intersection of two hyperboloids. This is a line extending upward (and downward) from the plane established by the three Loran stations. Thus a user must know his altitude in order to establish his horizontal position. The balance of the discussion above is valid for users at or near sea level. Corrections for users at higher altitudes are easily made.



Source: Reference II-4

Figure 7. Typical Loran Transmitter Configuration with Hyperbolic Lines of Position

It can be shown that the line of constant time difference is a hyperbola.⁶ Thus, the set of values of constant measured time differences from any two stations will establish a family of hyperbolae. When two pairs of stations are used, the two families of hyperbolae intersect to form a grid, as shown in Figure 7. Thus, Loran is known as a "pulsed, hyperbolic, grid-laying navigation system."

⁶ This is strictly true only for a flat earth. For typical Loran ranges it is a good approximation and, as will become apparent later, it makes no significant difference in the position-finding capability of Loran.

In actual practice, the master and slave stations do not transmit simultaneously. Instead, the signals from the slave stations are delayed so that the signals are always received in the same order (Master \rightarrow Slave X \rightarrow Slave Y \rightarrow ...) anywhere in the coverage area. These constant delays are included in the values shown on Loran grid coverage charts (see Figure 8, which shows a fixed delay of 28,580 μ s for Slave X), or are subtracted during processing in fully automated receivers.

C. LORAN ERRORS

Two sources of error in early Loran systems, transmitter timing errors and operator errors, have largely been eliminated. In Loran-A, all stations were crystal-controlled. The master station was free-running, and the slaves received the master signal and synchronized their timing to it. In current Loran-C systems, all stations have three or more Cesium-beam frequency standards and all stations, both master and slave, are free-running. As a result, timing errors are nonexistent. For example, records monitored on the Southeast Asia Loran-C chain over a period of several years show a mean timing error of less than 10 nanoseconds (ns), with a standard deviation of 15 ns. This results in a grid stability of about 10 meters.

Also, in Loran-A the operator measured the time delays by manually superimposing pairs of pulse envelopes on a CRT display. Using these values, he then interpolated on a Loran chart (similar to Figure 8) to find two LOPs and his position. The manual superposition had an inherent error of about 0.5 μ s, and the whole process was subject to unpredictable human errors. In current Loran-C systems, envelope matching has been replaced by cycle matching (to be discussed later), and the entire process of measuring time differences and converting to actual position has been automated to the point where the user is given a continual readout of his position in either Lat/Long or UTM coordinates.

However, certain fundamental limitations to the accuracy of Loran (or any other hyperbolic system) still exist, and the repeatable accuracy of Loran is dependent upon the user's position within the Loran coverage area. This effect is called Geometric Dilution of Precision (GDOP) and is due to a combination of two factors: divergence and crossing angles of the LOPs. Refer again to Figure 8 and note that a constant difference in the time differences between the LOPs (10 μ s in this case) corresponds to a position difference of 1 nmi near the baseline and to a difference of 8 nmi near the baseline extension. This divergence of adjacent hyperbola, or gradient effect, means that any given error in the measurement of τ_{xM} and τ_{yM} will yield different errors in the apparent position at different

points on the grid, that the positional errors will increase with increasing distance from the baseline, and that the errors increase faster in the direction of the baseline than in the direction normal to it.

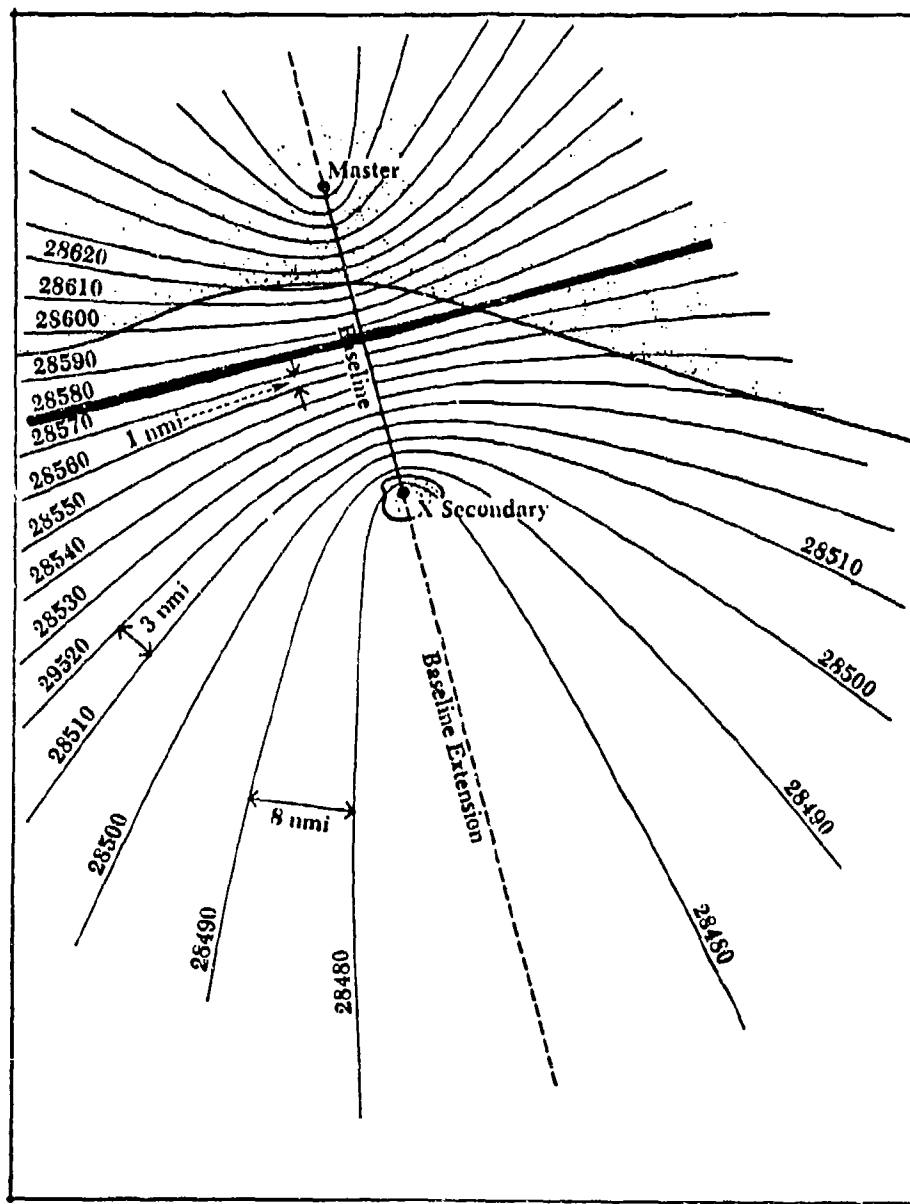


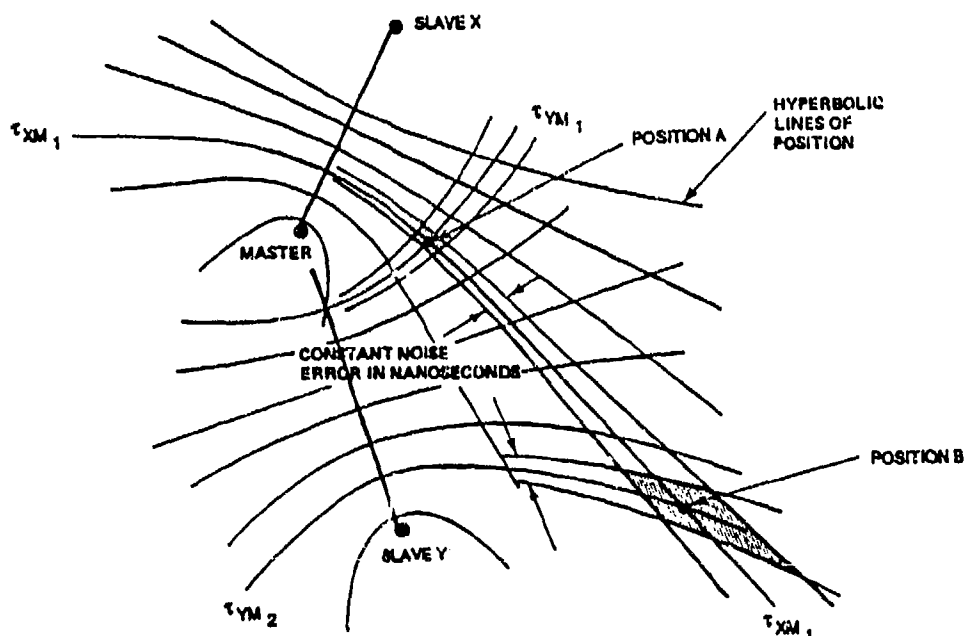
Figure 8. Partial Loran Chart
(only one set of hyperbolae shown)

In addition, whenever two non-orthogonal errors (such as the errors in measuring τ_{XM} and τ_{YM}) are combined into a two-dimensional error measure, the resulting error will depend on the angle between the two one-dimensional errors. If $\Delta\tau$ is a small error in the measure of τ , then the corresponding distance error Δd is given by:

$$\Delta d = \frac{\Delta\tau c}{2 \sin \Theta} \quad (11-1)$$

where c is the speed of light, and Θ is one-half of the angle between the lines connecting the point of measurement P with the two stations which are used to compute τ . This angle is referred to as the crossing angle and is the second factor in the GDOP effect. As the distance from the baseline increases, this angle becomes smaller, and the uncertainty in position (in two dimensions) becomes larger.

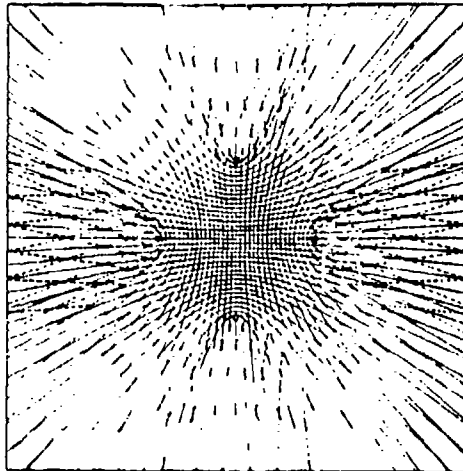
The result of both divergence and crossing angles is shown in Figure 9. Note that for constant measurement errors, the uncertainty of Position B (shown by the shaded area) is significantly greater than that of Position A.



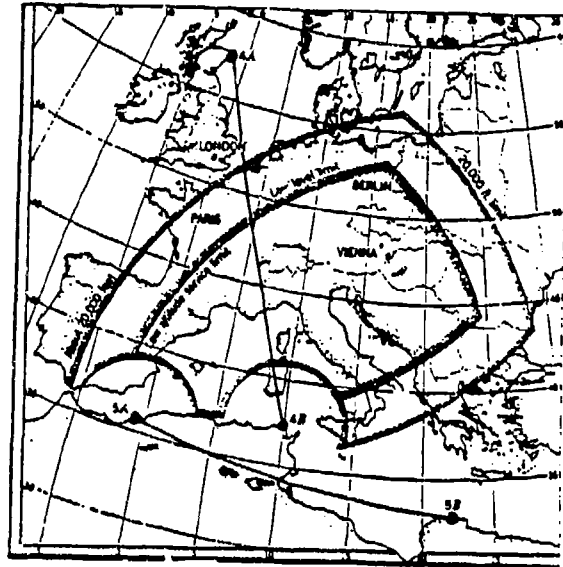
Source: Reference 11-1

Figure 9. Hyperbolic Geometric Dilution of Precision (GDOP)

The amount of GDOP is, of course, dependent on the geometry of the stations forming the Loran chain. It is minimized if four stations are used, located at the corners of a square encompassing the area to be covered. This is shown in Figure 10a, which is a theoretical calculation and in Figure 10b, which is the configuration of stations used to provide skywave Loran coverage over Europe in World War II.



(a) Theoretical



(b) Skywave Coverage of Europe by Stations in Scotland, Algeria, Tunisia, and Libya

Source: Reference II-8

Figure 10. Loran Grid for Square Configuration of Transmitters

D. LORAN WAVEFORM

In selecting the proper frequency for a radio navigation system, to give wide coverage and high accuracy, various physical factors must be considered. The basic limitation on accuracy is the velocity of propagation of radio energy: approximately 1 foot per nanosecond (1 ft/ns). Thus, for accuracies on the order of tens or hundreds of feet, time difference measurements must be made to accuracies of tens or hundreds of nanoseconds, and the propagation conditions must be predictable and repeatable (mathematically or from survey) enough to permit these accuracies:

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- Very Low Frequency (VLF) signals propagate primarily by the waveguide mode, and the predictability of propagation time suffers from the lack of real-time knowledge of ionospheric conditions.⁷
- Low Frequency (LF) groundwave signals, such as those used for Loran-C and -D, meet the requirements for stability, for measurement accuracy, and for ability to repeatedly predict groundwave propagation, although they are subject to skywave interference at very long ranges.
- Medium and High Frequency (MF and HF) signals, such as those which were used for Loran-A, meet the time measurement capabilities but suffer high propagation losses over land, thus reducing their range. They also suffer loss of propagation predictability due to natural and manmade physical features whose size can become a significant fraction of a wavelength.
- Higher frequency signals (VHF and above) are range limited to line-of-sight.

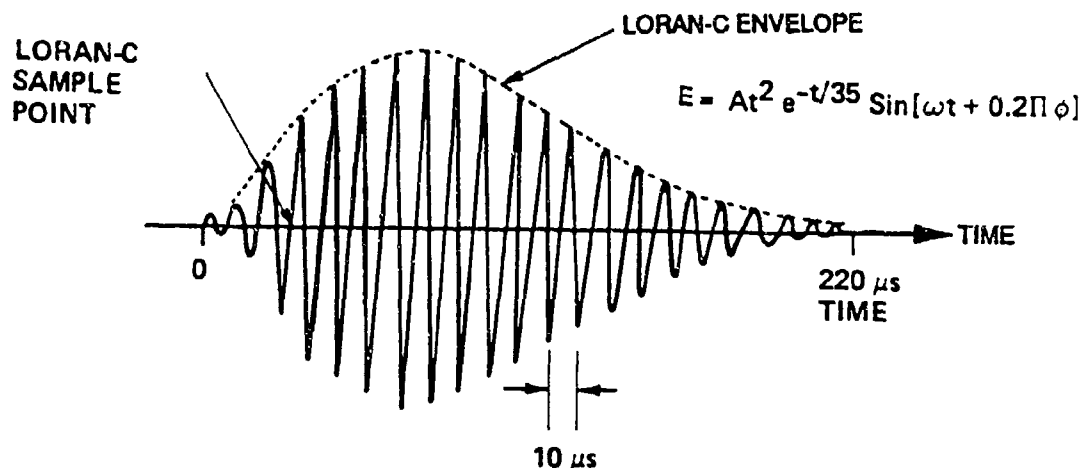
Thus, 100 kHz was chosen for Loran-C and -D to take advantage of the stable propagation and long-range characteristics of the LF band. Pulsed and phase-coded signals are used to minimize the effects of skywave interference.

Skywaves are echoes of the transmitted pulses that are reflected from the ionosphere. Skywave conditions vary from day to night and in different parts of the world. A skywave may arrive at a receiver as little as 35 μ s or as much as 1,000 μ s after the groundwave. In the first case, the skywave will overlap the last part of the groundwave pulse. For longer delays, the skywave may interfere with succeeding groundwave pulses. Either case will cause distortion of the received signal in the form of fading and pulse shape changes. Large positional errors could result if these conditions were not accounted for in the selection of the Loran-C/D signal format, and the design of the receivers.

The early arriving skywave can be overcome by making time-of-arrival measurements on the first part of the pulse. This is enhanced by using a pulse with a rapidly rising leading edge, so that significant pulse amplitude is present before the skywave arrives (see Figure 11).

⁷ See the discussion of the Omega system of radionavigation in the next chapter of this paper.

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Source: Reference II-1

Figure 11. Loran-C Waveform

This waveform is maintained to very precise tolerances. The time of transmission, the carrier frequency, and the carrier phase are all controlled by Cesium-beam frequency standards. The shape of the pulse envelope is also carefully controlled, since it is used by the receiver to identify one particular cycle of the 100 kHz carrier.⁸ This is essential to prevent whole-cycle ambiguities in the time difference measurements and allows the high accuracy of the phase measurement system to be maintained. A one-cycle measurement error would be 10 μs, or about 1.6 nmi. As shown in Figure 11, the sample point for Loran-C is the positive-going axis crossing of the third cycle, at a point 30 μs into the pulse.

The transmitted pulse format for Loran-C is shown in Figure 12.

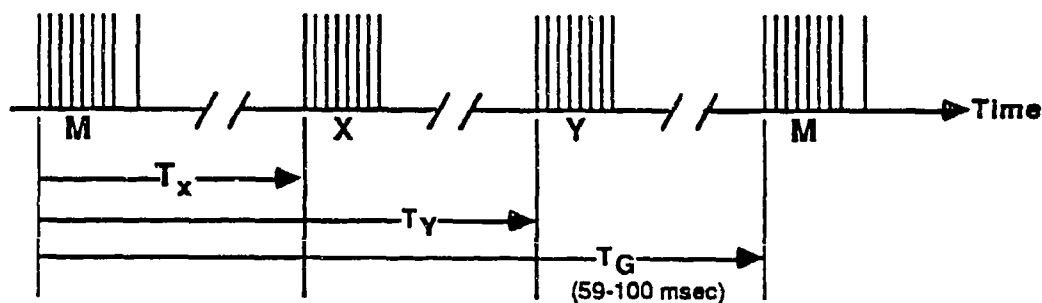


Figure 12. Loran-C Pulse Format

⁸ Identifying the correct cycle is critical since, as noted above, a one-cycle measurement error results in a location error of about 1.6 nmi. The shape of the envelope is designed to assist in this process. If the envelope function ($E_{env}(\tau) = A\tau^2 e^{-\tau/35}$) is subtracted from its derivative, the resulting waveform ($E_{env} - E_{env}'$) crosses the zero axis at $\tau = 19.44 \mu\text{sec}$ and provides a reference point which is independent of the received signal amplitude.

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The master station transmits the pulse shown in Figure 11 nine times, with the first eight pulses spaced $1,000 \mu\text{s}$ (1 ms) apart, and the ninth pulse $2,000 \mu\text{s}$ after the eighth. After a fixed delay, T_X , Slave X transmits a series of eight identical pulses at intervals of $1,000 \mu\text{s}$ and, after a fixed delay of T_Y , Slave Y repeats the process. The entire process repeats after a delay T_G which is determined by the Group Repetition Interval (GRI). This will be discussed later.

Multiple pulses from each transmitter are used to provide more energy to Loran receivers (to improve the signal-to-noise ratio), to provide a larger sample size (to improve accuracy), and to help in reducing skywave degradation. The ninth pulse sent by the master station is used to aid in identifying the master and can also be modulated to pass information among the stations in the Loran-C chain.⁹

To prevent the long-delay skywaves from affecting the time difference measurement, the phase of the 100 kHz carrier is changed in each pulse of a group in accordance with a predetermined pattern. The phase codes for Loran-C are shown in Table 2. In addition, the phase code is different for the master and slave signals so that automatic receivers may use the code for master and slave station identification.

Table 2. Loran-C Phase Codes

	Master									Each Slave							
Period	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8
GRI A	+	+	-	-	+	-	+	-	+	+	+	+	+	+	-	-	+
GRI B	+	-	-	+	+	+	+	+	-	+	-	+	-	+	+	-	-

Receiver designers have worked hard to develop and implement techniques to recognize and discard the skywave since it interferes with accurate Loran navigation. However, even the Loran skywaves contain potential information which, although somewhat degraded in accuracy, can be used for general area navigation. The fact that hyperbolic Loran depends upon the time difference--and not the absolute time of signal propagation--provides for some cancellation of the variations in path length caused by

⁹ Until recently, the ninth pulse was "blinked" off and on in specified codes to indicate an out-of-timing-tolerance condition for the master station or one or more of the slaves. This is no longer done. The current warning scheme will be discussed later.

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ionospheric reflection. Although the variation is not totally cancelled, the resulting accuracies can be quite acceptable for area navigation.

The transmitting stations of a Loran-C chain transmit groups of pulses at a specific GRI. For each chain, a minimum GRI is selected of sufficient length to ensure transmission of the pulse groups (10 ms for the master and 8 ms for each slave) from each station group so that signals from two or more stations cannot overlap anywhere in the coverage area. The minimum GRI is, therefore, a direct function of the number of stations and the distance between them. A specific GRI for the chain is then selected so that nearby chains cause a minimum of mutual (cross-rate) interference. Possible values for GRI are listed in Table 3. The GRI is defined to begin coincident with the start of the first pulse of the master group.

Table 3. Group Repetition Intervals

Specific GRI	Basic GRI				
	Loran-C Only			Loran-C and Loran-D	
	SS	SL	SH	S	L
0	100,000	80,000	60,000	50,000	40,000
1	99,900	79,900	59,900	49,900	39,900
2	99,800	79,800	59,800	49,800	39,800
3	99,700	79,700	59,700	49,700	39,700
4	99,600	79,600	59,600	49,600	39,600
5	99,500	79,500	59,500	49,500	39,500
6	99,400	79,400	59,400	49,400	39,400
7	99,300	79,300	59,300	49,300	39,300

NOTE: 1. GRI in μ s

- The designation of a chain GRI is a combination of the identification of the basic and specific GRI. For example, SL-7 designates a chain having a GRI of 79,300 μ s.
- Originally, the Loran pulse repetition rates were identified as S (slow: 20 pps), L (low: 25 pps), and H (high: 33-1/3 pps). The H rate is no longer used and three other rates (SS, SL, SH), each with a period twice as long as its original counterpart, were added later.

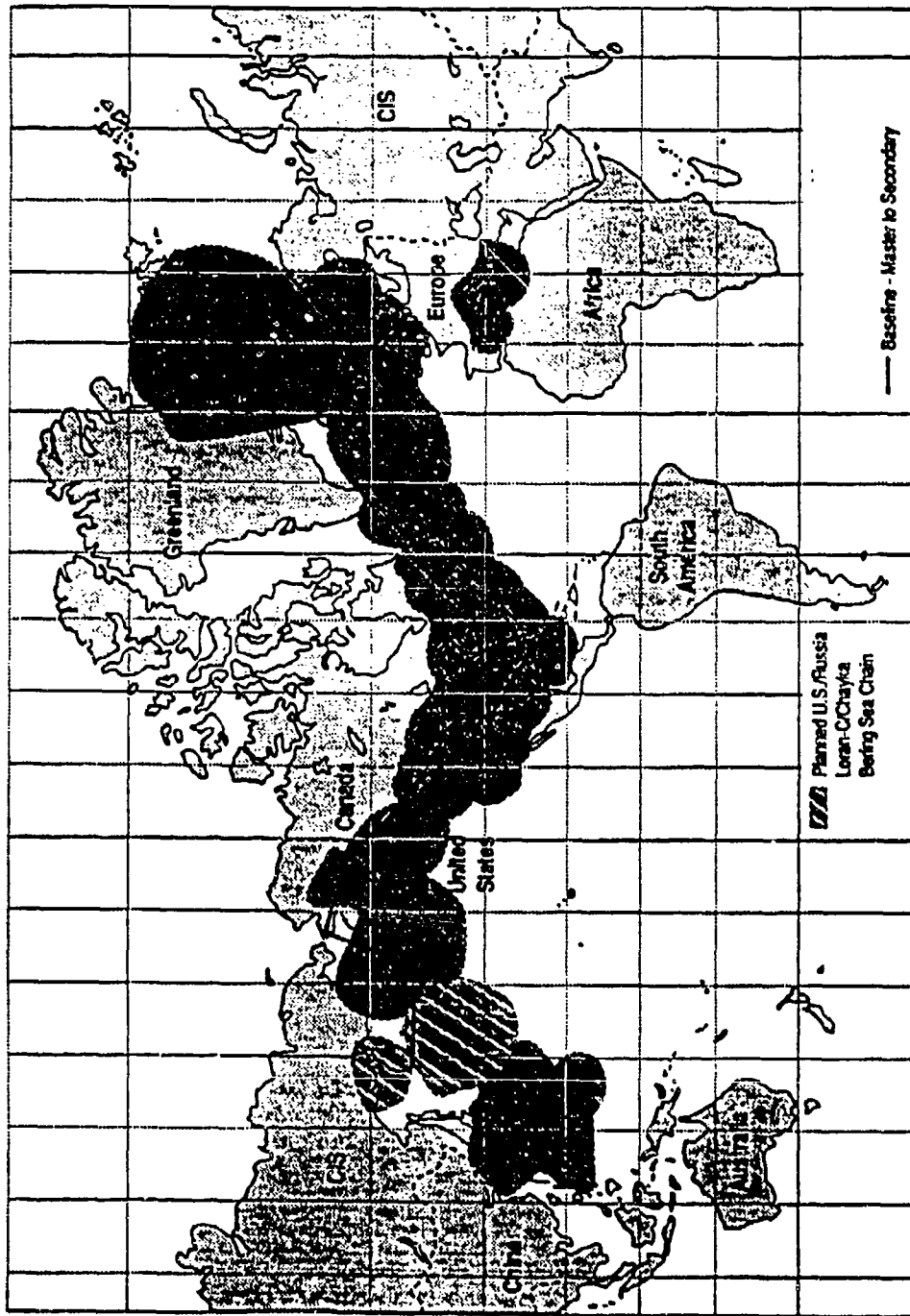
E. LORAN COVERAGE

The U.S. Coast Guard now operates or controls a worldwide network of 46 Loran-C transmitter stations which are formed into 18 chains. These provide the coverage shown in Figure 13.

By 1994, the Coast Guard will cease to operate the Loran-C stations located on foreign soil and will be responsible only for a reduced set of 28 stations (12 chains). Most of the other stations will be taken over by other countries and will remain in operation. The coverage shown in Figure 13 will remain essentially unchanged, although there will be some reductions in the North Atlantic and in the Greenland-Iceland area.

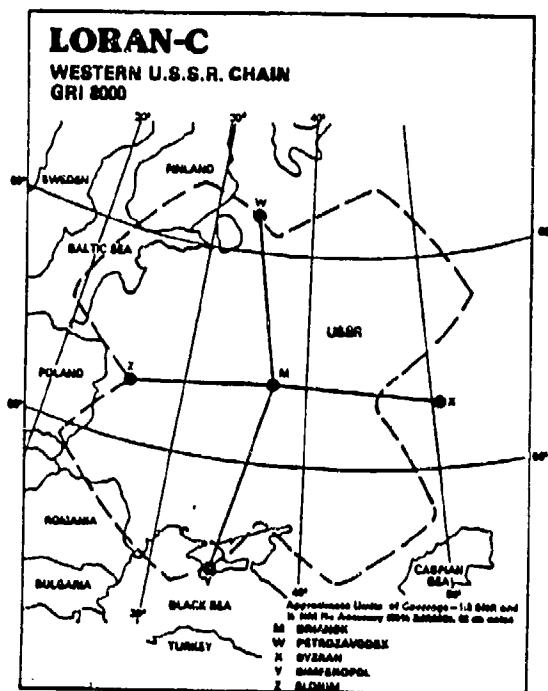
In addition to the coverage now provided by the Coast Guard, several Loran-C chains are operated entirely by foreign governments. These are shown in Figure 14.

The stations in these chains use the standard Loran-C format and can be used by any Loran receiver, either as part of their own chains or in combination with stations from other chains. However, since they are operated by foreign governments, the Coast Guard does not monitor them and will not guarantee their accuracy.

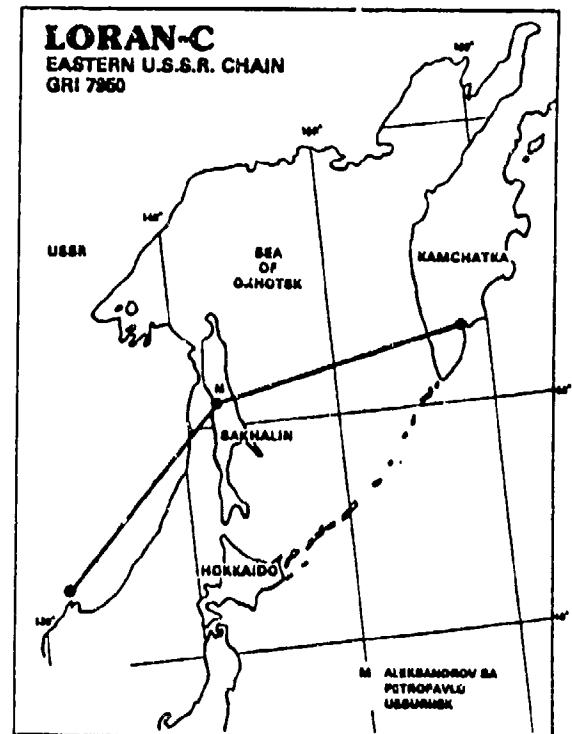


Source: Reference II-2

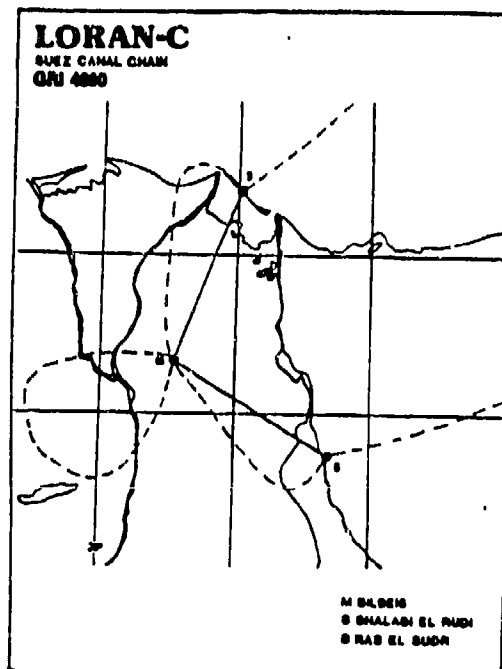
Figure 13. Worldwide Loran-C Coverage by U.S. Coast Guard



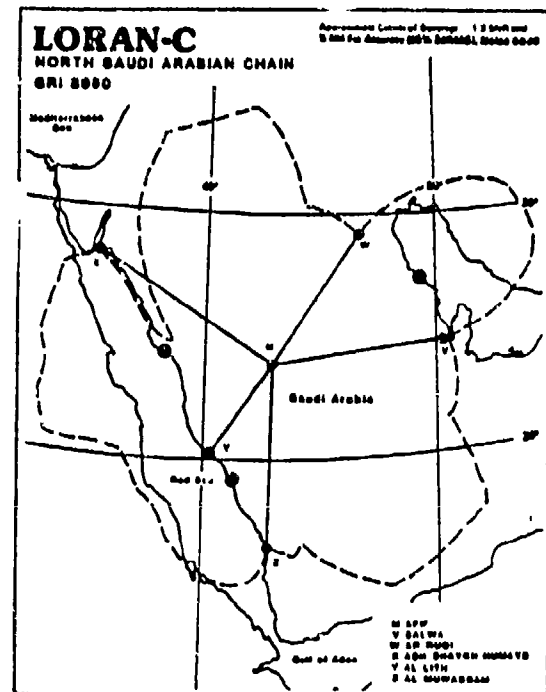
(a) Western Russian Chain



(b) Eastern Russian Chain

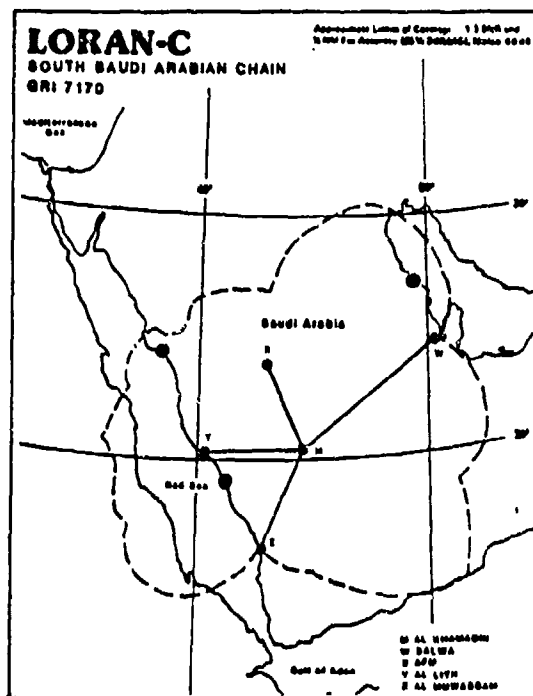


(c) Suez Canal Chain



(d) North Saudi Arabian Chain

Figure 14. Other Loran-C Chains



(e) South Saudi Arabian Chain

Source: Reference II-9

Figure 14. (continued)

F. LORAN PERFORMANCE

Loran-C chains consist of a master transmitting station, two or more slave transmitting stations and, if necessary, System Area Monitor (SAM) stations. The transmitting stations are located such that the master and at least two slave stations can be received throughout the desired coverage area. For convenience, the master station is designated by the letter "M" and the slave stations are designated X, Y, Z, W, T, based on the order in which they transmit.

All transmitting stations are equipped with atomic clocks using Cesium-beam frequency standards, which are accurate to 1 part in 10^{12} or better. The high stability and accuracy of these standards permit each station to derive its own time of transmission without reference to another station. This is called the "free-running" mode of operation. All stations, both master and slave, are operated in free-running mode, although they are periodically compared and any necessary corrections are made.

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The objective for control of a Loran-C chain is to maintain constant the observed Time Difference (TD) of each master-slave pair at any particular point in the coverage area. Frequency offsets in the Cesium standards and changes in propagation conditions can cause the observed TD to vary. Therefore, one or more SAM stations with precision receiving equipment are established in the coverage area to continuously monitor the TDs of the master-slave pairs. In some cases a transmitting station is suitably located and performs the SAM function. A control TD is established thorough calibration and, when the observed TD varies from the control TD by one-half of the prescribed control tolerance, the SAM directs a change in the timing of the slave station to eliminate the error. The control tolerance is 50 ns for precision chains and, since the process of adjusting the timing is under computer control, the average error in timing is usually on the order of 25-30 ns. If the observed error is more than 100 ns, the affected slave station will "blink" its first two pulses by turning them on for 0.25 seconds in a 4-second period and off for the rest of the period. This blinking, which is continued for as long as the error exists, advises the user that a timing error exists.

Using groundwaves, reliable operating ranges of 800-1,200 nmi from each transmitter are typical, depending on transmitter power, environmental noise, and losses over the signal path.

All Loran-C stations have redundant transmitting, timing, and control equipment. Individual station reliability exceeds 99.9 percent and chain availability exceeds 99.7 percent.

Loran error sources can be divided into two general categories:

- **Random Errors** result from such things as clock jitter, atmospheric noise, and receiver front-end noise. These are generally zero-mean random processes and will average out over time.
- **Bias Errors** result from such things as clock offsets, changes in propagation constants (e.g., changes in the moisture content of the land surface over which the wave is passing), incorrectly determined primary or secondary phase factors, or, in the case of skywave propagation, changes in the ionosphere. These errors tend to be fixed or slowly varying.

The accuracy of Loran-C is best near the center of the coverage area where the signal-to-noise ratio (S/N) is high and where the geometry is such that the GDOP is minimized (see Section C and Figure 9). At the edges of the coverage area, the accuracy is

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poorer because the S/N is lower, the GDOP is higher, and the uncertainties in propagation velocity and propagation delays will increase with increasing path lengths.

Three types of accuracy are used to describe the performance of Loran and other navigation systems:

- **Predictable Accuracy** (also called absolute or geodetic accuracy) is the accuracy of a measured position with respect to an established grid system such as Lat/Long or UTM. Both random errors and bias errors effect predictable accuracy.
- **Repeatable Accuracy** is the accuracy with which a user can return to a position whose coordinates have been measured at some previous time, using the same navigation system. Repeatable accuracy will always be better than predictable accuracy because the bias errors tend to remain constant over time and will at least partially cancel out between the two repeated measurements.
- **Relative Accuracy**¹⁰ is the accuracy with which two users can measure their positions with respect to each other, using the same navigation system at the same time. In this case, the bias errors cancel completely and the highest possible accuracy is realized.

The predictable accuracy of Loran-C will be 0.1 nmi (185 meters) or better at ranges up to 500 nmi from the center of the grid, and will increase to 0.25 nmi (460 meters) at ranges up to 1,000 nmi. It should be noted, however, that all Loran-C stations are free-running and independent and that there is no requirement to use only stations from a single chain. In areas where many stations exist, such as Europe or the continental United States, it is almost always possible to pick three or more stations with good signal strength and good geometry (low GDOP) and to realize "center of the grid" accuracies anywhere in the area. In fact, the modern Loran receivers used by both commercial and private aircraft perform this station selection automatically.

The repeatable accuracy of Loran-C varies from 20 meters or less near the center of the grid to 100 meters at the edge of the coverage area, and the relative accuracy is 10-20 meters.

¹⁰ See the discussion of Differential Loran in Section G.

G. DIFFERENTIAL LORAN

The fundamental physical limitations to the accuracy of Loran-C are GDOP, random errors, and unpredictable and/or uncorrected propagation anomalies of the LF signal. These propagation anomalies may be periodic and, to some extent, correctable, or random (resulting, for example, from weather or solar flares) and uncorrectable. In either case, the accuracy of the system may be enhanced by using a technique called Differential Loran. A Differential Loran station is established at a precisely known location. The station measures the instantaneous local propagation variations by comparing the received Loran signals with those expected for its known location. Corrections to the measured Loran time differences are then calculated and broadcast to users in the vicinity of the Differential Loran station. This process, in effect, recalibrates the system and restores the accuracy to that which would be expected near the baselines of the Loran-C chain. This technique is now used for river and harbor navigation and, out to a radius of 50-100 miles from the Differential Loran station, provides the 10-20 meter accuracy which is required.

H. LORAN-D

Loran-C stations are fixed, permanent installations intended to provide long-term coverage of preselected areas. At the same time that the Navy and Coast Guard were developing Loran-C, the Air Force was developing a transportable system called Loran-D. The theory of operation is exactly the same as for Loran-C and, over their respective areas of coverage, the performance and accuracy are identical. However, certain compromises had to be made in order to make Loran-D transportable: the transmitter power is lower, the antenna is smaller, and transmitted group consists of 16 pulses rather than 8 in order to partially compensate for the lower power. The characteristics of Loran-C and Loran-D are compared in Table 4.

There is only one Loran-D chain in existence at the present time. It is located at Fort Hood, TX, but could presumably be moved if conditions warranted.

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Table 4. Comparison of Loran-C and Loran-D

Parameter	Loran-C	Loran-D
Carrier Frequency	100 kHz	100 kHz
RF Bandwidth	20 kHz	17 kHz
Frequency & Timing Control	Cesium-beam	Cesium-beam
Transmitter Power	165 - 2,160 kW peak ^a	40 kW peak
Pulses per Group	8	16
Spacing between Pulses	1,000 μ s	500 μ s
Groundwave Range	800-1,200 nm	250-400 nm

^a Depends on station and area to be covered

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III. OMEGA

A. HISTORY

"Radar Aids to Navigation," the second volume of the MIT Radiation Laboratory Series was published in 1948 and contained a section on Loran by Professor J.A. Pierce of Harvard University. In it he discussed the performance and limitations of Loran-A (at 2 MHz) and low-frequency Loran (at 180 kHz), both of which used envelope-matching to determine lines of position (LOP). Toward the end of the section, Professor Pierce wrote the following prophetic paragraphs, which presaged not only the use of cycle-matching for Loran but also the use of continuous-wave (CW) signals for Omega:

A version of LF Loran which may become extremely important, at least for certain applications, is called "cycle matching;" it consists of comparing the phase of the r-f or i-f cycles of a pair of pulses rather than of comparing the envelopes of the two pulses. Equipment for this technique is still in such an early stage of laboratory development that a critical evaluation is not yet possible; it seems reasonable, however, to expect that measurements may be made to 0.1 msec over ground-wave ranges.

As long as current techniques prevail, therefore, pulse methods cannot be expected to operate at these [very low] frequencies. At present it seems that 100 to 150 kc/sec is about the lower limit for pulse systems. At these frequencies ranges of 1500 miles should be easily obtained over land or sea and at any altitude. Either pulse or continuous-wave systems may be used at these frequencies, although the pulse systems will require larger and more expensive antenna structures. If reliable ranges greater than about 1500 miles are needed, continuous-wave systems operating at very low frequencies must be used. The alternative is to use pulse systems with very long pulses and relatively low accuracy [Ref. III-7].

The first experimental long-range continuous wave (CW) navigation systems was called Radux, and operated in the vicinity of 50 kHz, with 200 Hz sine-wave modulation. The navigator's LOP was determined from phase differences measured at the modulation frequency. Radux stations were established in California and Hawaii, and the system demonstrated root mean square (rms) fix accuracies on the order of 5 miles¹ at ranges in

¹ This corresponds to a phase measurement accuracy of about 0.5 percent at the modulation frequency of 200 Hz.

excess of 2,000 miles. In 1955, a system was demonstrated that combined the LF signals of Radux with a separate VLF signal at 10.2 kHz. The system was called Radux-Omega and used phase-difference measurements at the carrier frequency of the 10.2 kHz signal to provide more accurate LOPs than with Radux alone. Subsequent experimentation led to discontinuance of the LF Radux portion of the signal.

In 1957, preliminary work began on an all-VLF system called Omega and by 1964, four experimental stations, operating at both 10.2 and 13.6 kHz, were operating from Hawaii, the Panama Canal Zone, New York, and Wales. Stations in Norway and Trinidad were added later.

The U.S. Navy established an Omega Project Office in 1965 to develop and implement an all-weather, worldwide radio navigation system. Six bilateral agreements were negotiated to permit the establishment of Omega stations on foreign soil. Operational control was passed to the U.S. Coast Guard in 1979, and the Omega system became fully operational with the completion of the eighth and final transmitting station in Australia in 1982.

B. FREQUENCY SELECTION AND PROPAGATION²

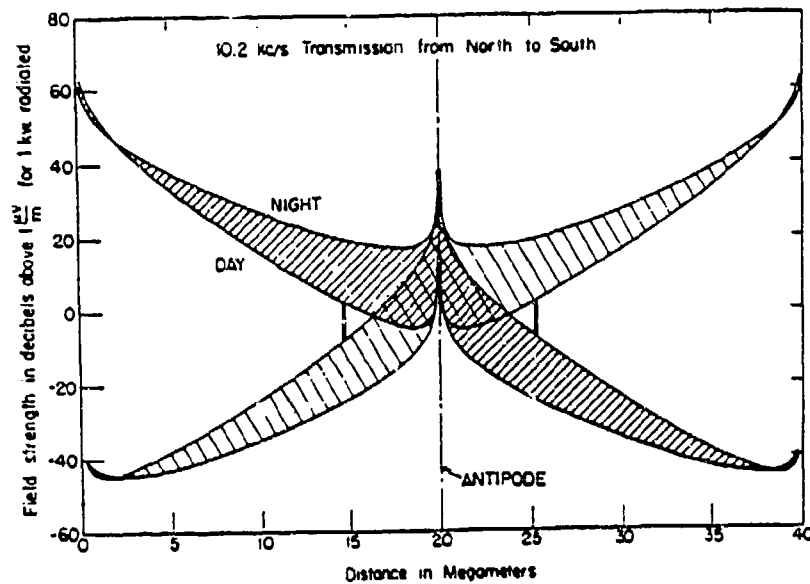
Omega operates in the internationally allocated VLF navigation band from 10 to 14 kHz. VLF signals propagate in the concentric spherical waveguide formed between the earth's surface and the D-layer of the ionosphere at an altitude of 40-70 nmi. The Omega frequency band is optimum for achieving single-mode propagation in this spherical waveguide: at frequencies much below 10 kHz, transmission is near the waveguide cutoff, at least during daytime, resulting in high attenuation and a phase velocity that may be too far above the speed of light to permit accurate prediction of phase. At frequencies above 20 kHz, on the other hand, higher order modes will be propagated. The second-order mode at 20 kHz, for example, may dominate the field for the first 2,000-3,000 km, and may be nearly equal to the first-order mode for distances much longer than that. This results in phase perturbations that vary with time (due to the changing position of the D-layer) and are difficult to predict with accuracy.

Since the VLF waves are confined to the spherical waveguide, there is very little loss, and the attenuation constant is low. However, the attenuation for a wave traveling

² Some of the material in this section has been adapted from the Coast Guard *Omega Guide for Users* (Reference III-5).

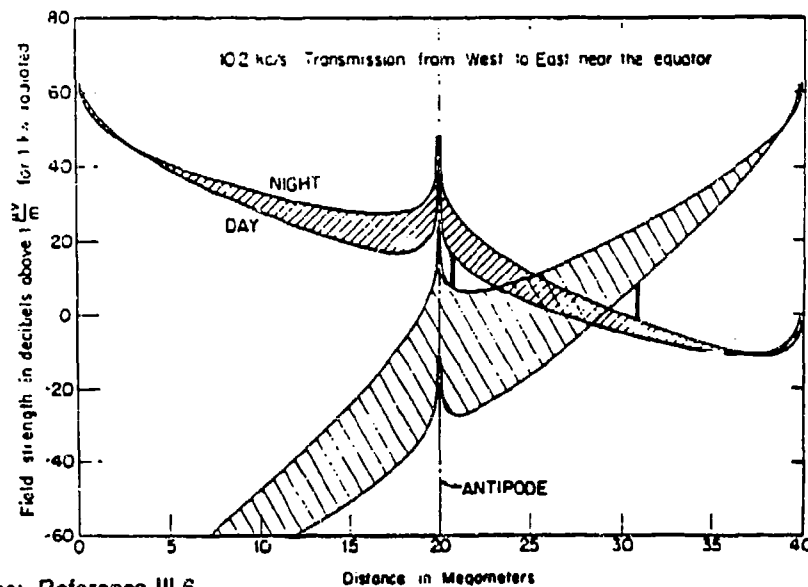
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from east to west at the geomagnetic equator is more than twice that of one traveling from west to east, because of interactions with the horizontal component of the earth's magnetic field. This is shown in Figures 15a and 15b.



Source: Reference III-6

Figure 15a. Field Strength at 10.2 kHz as a Function of Distance for Transmission Along the Earth's Magnetic Field



Source: Reference III-6

Figure 15b. Field Strength at 10.2 kHz as a Function of Distance for Transmission from West to East. For Transmission from East to West, Reverse the Distance Scale

In each figure, the heavily shaded band shows the field strength at the distances [in megameters (Mm)] shown on the abscissa. The lightly shaded band shows the strength of a signal propagated in the opposite direction around the world. The average attenuations are shown in Table 5.

Table 5. Attenuation of VLF Signals in Waveguide Mode³

Direction of Propagation	Attenuation (dB/Mm)
East to West	4.5
West to East	1.6
North to South	2.6
South to North	2.6

The vertical bars in Figures 13a and 13b show the ranges at which the two signals (short-way and long-way propagation paths) are within 10 decibels (dB) of each other and might interfere sufficiently to cause measurement errors. It can be seen that in the north-south direction, the short-way signal remains usable (10 dB or more above the long-way signal) to a distance of nearly 15 Mm. At the geomagnetic equator, the east-to-west short-way signal is usable to only about 9 Mm,⁴ while the west-to-east signal is usable to more than 20 Mm. These values are more than adequate to provide worldwide coverage from eight Omega stations.

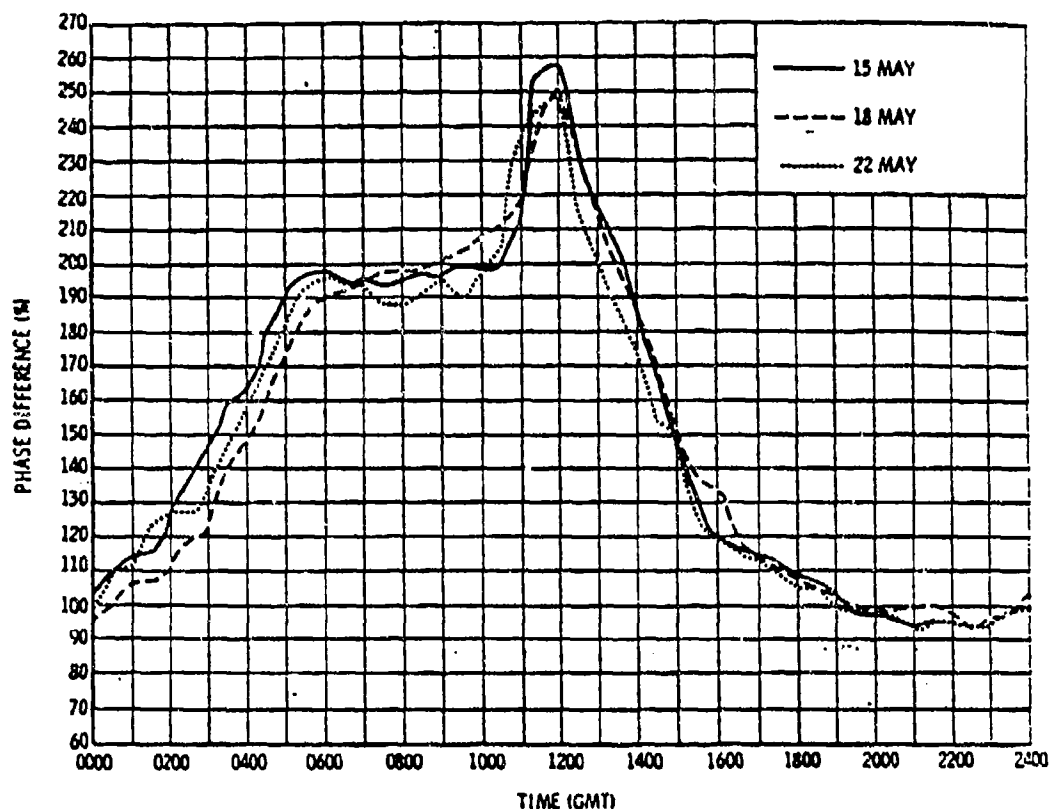
However, the waveguide propagation of VLF signals does have some drawbacks. Since the ionosphere is created, in part, by the action of solar radiation, the day and night ionospheres differ significantly both in height and in the density of charged particles. This affects not only the attenuation of the Omega signals but also the velocity of propagation and thus the wavelength. The variation in attenuation is indicated in Figures 15a and 15b, where the night and day values define the edges of the bands. This effect can generally be ignored, however, since the S/N ratio will remain adequate under all conditions.

³ These remarkably low values are due to the waveguide effect, which keeps the wave from spreading. In free space, the loss would be about 53 dB/Mm.

⁴ "Only about" 5,000 nautical miles, or one-quarter of the circumference of the earth.

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The diurnal variation of the velocity of propagation through the waveguide is a more serious concern since it changes the wavelength of the VLF signal and, therefore, the relative phase measured by a user. An example of this is shown in Figure 16.



Source: Reference III-9

Figure 16. Observed Diurnal Variation in Phase Shift for 3 Days at Whidbey Island, WA, May 1962

Although the diurnal phase variation is large (more than a complete cycle in this case), it is seen to be repeatable and consistent. It can be predicted accurately (to within a few percent in the example shown) and corrections to actual Omega readings can be easily made.

During daytime, the ionospheric reflection height for Omega signals is approximately 43 nmi and is quite consistent. For a path where both the transmitter and receiver are in the daytime hemisphere, the signal path phase shift can be predicted to an

equivalent of ± 5 Cec.⁵ At night, the reflection height rises to about 55 nmi and becomes less consistent, and prediction accuracies for all night side signal paths are reduced to ± 10 Cec. Signal paths for which the sunrise or sunset line lies between the receiver and transmitter encounter an additional loss in prediction accuracy as a result of the transition of the ionosphere from its daytime to nighttime configuration at this boundary. If the signal path is on a generally north-south line, the transition period is of short duration, and accuracy is poor during the transition period. For a generally east-to-west signal path, the transition interval is much longer and the prediction error is less since the phase change is more gradual. In either case, the day and night phase velocities may be so different that the phase can pass through a complete cycle during the day-night transition. Fortunately, these diurnal effects are well understood and accurately predictable. They are published in Propagation Correction (PPC) tables which list the day/night ionospheric height changes as well as the location of the sunrise/sunset lines with respect to the locations of the transmitter and receiver. The data may be used by an Omega operator to correct readings or may be included in the computer algorithm of an automatic receiver.

Although the diurnal variations in the ionosphere can be predicted with sufficient accuracy for the Omega system, the sudden and dramatic modifications in the normal ionosphere brought about by solar storms are not predictable either in terms of time, or duration of occurrence, or in terms of the effect on Omega signal path lengths. These propagation disturbances fall into three general classes:

- A **Sudden Ionospheric Disturbance (SID)** occurs when X-rays are emitted from the sun during a solar flare. This added ionizing radiation causes a lowering in the effective height of the ionosphere over the illuminated sunlit area and changes the Omega signal paths. A SID may cause LOP errors of 4 nmi or more at 10.2 kHz on the baseline of sunlit paths. These disturbances form in a matter of minutes after a solar flare begins and last from 45 minutes to 3 hours. Because of the rapid onset and short duration of a SID, navigational warnings are not issued.
- A **Polar Cap Anomaly (PCA)** is caused by the emission of high energy protons from the sun and influences the ionosphere at high latitudes. These protons are concentrated in the polar region by the earth's magnetic field and cause a reduction in height of the ionosphere, which affects the phase of transpolar Omega signals. The PCA occurs within a few hours after the

⁵ Omega phase measurements are customarily made in centicycles (Cec) rather than degrees. One centicycle is one-hundredth of an Omega "lane" which is, in turn, one-half of an Omega wavelength. At the primary Omega frequency of 10.2 kHz, a centicycle is 147 meters.

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appearance of a solar flare, usually lasts from 1 to 3 days, and may cause positional errors of up to 8 nmi at 10.2 kHz on the baseline for long transpolar paths. Omega notices or navigational warnings are issued by various means on the occurrence of PCAs.

- The third type of interference is **Modal Interference**, which causes irregularities to appear in the phase pattern of the Omega signal. The areas and time intervals subjected to modal interference are generally predictable, but the effects are not. Ideally, one propagation mode would be completely dominant at all times, and the resultant phase grid would be stable. In practice, competing modes do not completely disappear and three situations are recognizable: If the competing mode is very small, the dominant mode will establish a nearly regular phase pattern, as intended. This is usually what happens. A second possibility is that the competing mode may be almost equal to the dominant mode. The third, and most serious, case is that in which modal dominance changes. This may occur, for example, if one mode is dominant during the day and a second mode is dominant at night. Clearly, sometime during sunset and sunrise, the transitional period, the two modes must be equal. Depending upon the phasing of the modes at equality, abnormal transitions may occur in which lanes are "slipped" or lost. LOP errors of 8 nmi or more at 10.2 kHz on the baseline are possible under such conditions.

The importance of these sudden disturbances on the utility of the Omega system should not be understated. However, there are considerations that tend to mitigate their effect: First, most users will have more than one navigation system (Loran, Omega, inertial, celestial, etc.), with the outputs often combined to take advantage of the best features of each of the systems.⁶ The loss of one system for a short period of time should not be a serious problem. Second, two of the unpredictable anomalies (PCAs and Modal Interference) are long-term phenomena, and users are warned when they are occurring. Sudden ionospheric disturbances, on the other hand, build up within a few minutes and cause errors of 4 nmi or more. This sudden change in apparent position should be obvious to the navigator and should cause him to treat his Omega readings with caution until the disturbance subsides.

⁶ For example, Loran or Omega (which have good predictable accuracy) could be used to update an inertial system (which has good short-term smoothing but tends to drift over time).

C. THE OMEGA SYSTEMS

Omega is a CW, hyperbolic,⁷ grid-laying, worldwide navigation system operating on a set of VLF frequencies from 10 to 14 kHz. Because of the excellent propagation characteristics at VLF, the baseline between stations can be 5,000-6,000 nmi, and global coverage can be achieved with eight transmitting stations.

1. Omega Stations

The locations of the eight permanent Omega stations are shown in Table 6 and Figure 17.

Table 6. Omega Station Location

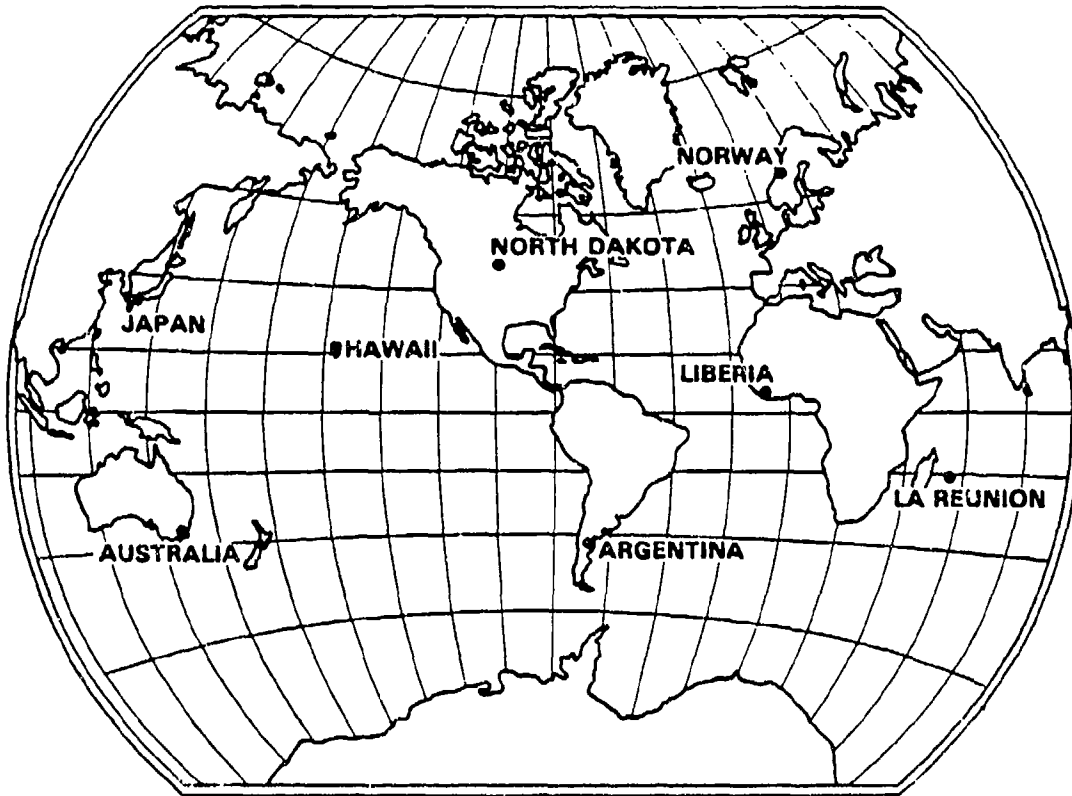
Location	Letter	Antenna	Unique Frequency (kHz)
Andra, Norway	A	Fjord Span	12.1
Monrovia, Liberia	B	Grounded 1400' Tower	12.0
Haiku, Oahu, HI, USA	C	Valley Span	11.8
LaMoure, ND, USA	D	Insulated 1200' Tower	13.1
La Reunion Island, France	E	Grounded 1400' Tower	12.3
Golfo Nuevo, Argentina	F	Insulated 1200' Tower	12.9
Woodside, Australia	G	Grounded 1400' Tower	13.0
Tsushima, Japan	H	Insulated 1500' Tower	12.8

At most sites, the antenna is a 1,200-1,500-foot top-loaded vertical tower. At two of the sites where the geography is suitable, a valley-span antenna is used: a vertical radiating feed line from the transmitter is connected to a series of wires stretched across a valley. The transmitter power is 150 kW CW. However, since the antennas are small compared to a wavelength (a 1,500-foot tower is about 1.5 percent of a wavelength at 10.2 kHz), the antenna efficiency is low, and the Effective Radiated Power (ERP) is 10 kW. The Omega system is operated by the U.S. Coast Guard. Control of stations on foreign soil is established by a set of six international agreements between the United States and the

⁷ Other techniques are also commonly used. This will be discussed later.

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other participating nations. Omega charts, propagation correction tables, and other documents are published by the Defense Mapping Agency.



Source: Reference III-5

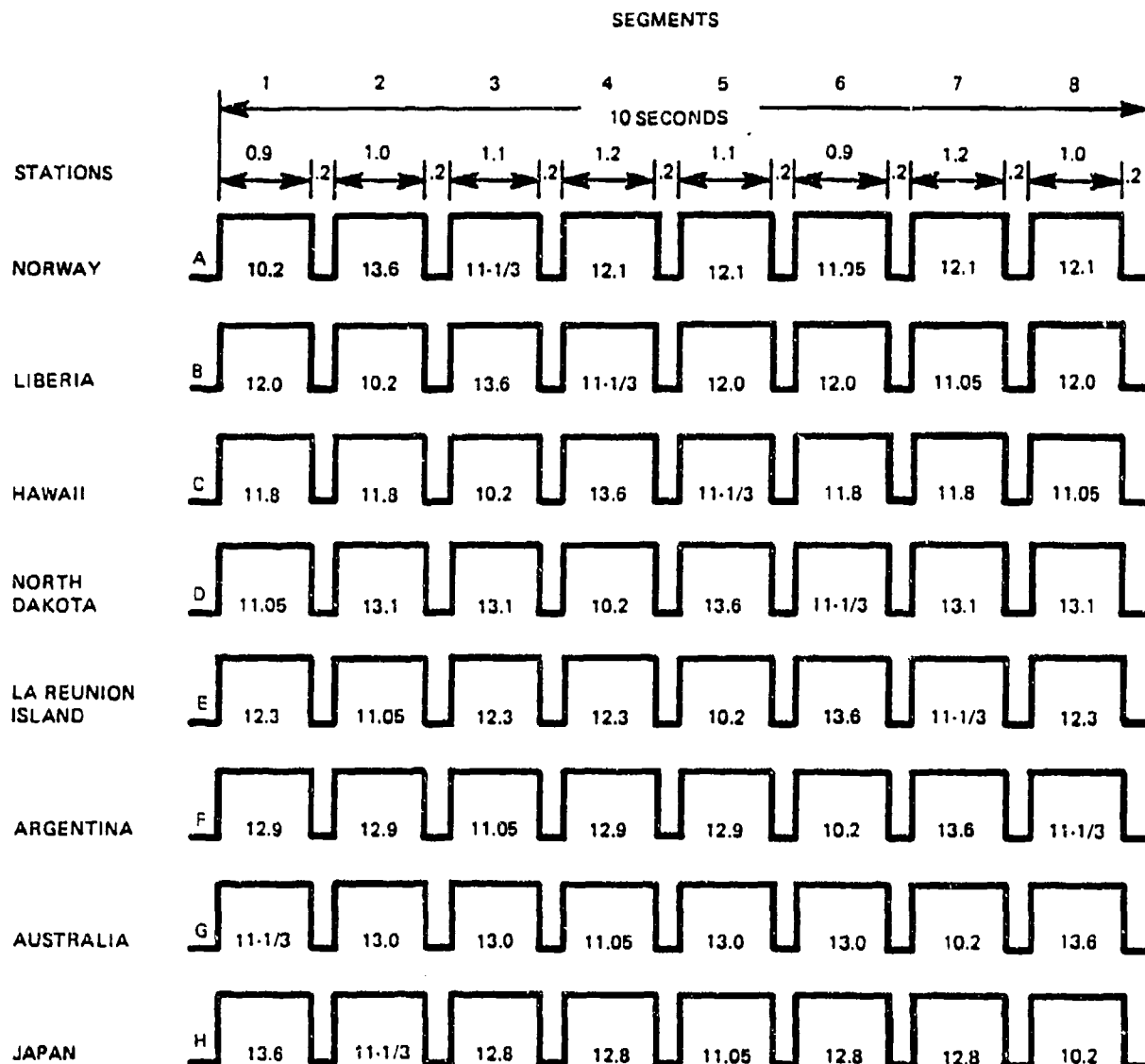
Figure 17. Omega Station Locations

2. Omega Signal Format

Each Omega station transmits a series of RF pulses ranging in duration from 0.9 to 1.2 seconds, with silent intervals of 0.2 seconds between each pair of pulses. Four navigation frequencies are transmitted (10.2, 13.6, $11\frac{1}{3}$, and 11.05 kHz), together with a fifth frequency that is unique for each station. The unique frequencies are listed in Table 6.

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18. The frequency patterns, which are also unique for each station, are shown in Figure



Source: Reference III-5

**Figure 18. Omega Signal Transmission Format,
Showing Transmitted Frequencies in kHz**

The patterns have been chosen so that no two Omega stations transmit the same frequency at the same time since, in this case, the receiver would be unable to distinguish one station from the other.

3. Timing and Synchronization

As with other navigation systems, the timing of Omega is very precisely controlled. Each station uses three Cesium-beam standards to establish its frequency reference and is synchronized to within 2 μ s of system time. System time is maintained to within 5 μ s of Coordinated Universal Time (UTC).⁸ Omega standard time commenced on 1 January 1972 at 00:00 hours Greenwich Mean Time (GMT). At that time, the phases of all Omega transmissions simultaneously passed through zero, moving in a positive direction.

The transmission periods shown in Figure 18 are controlled by keying pulses generated from the Cesium-beam standards. The keying-on pulses are accurate to within 1 μ s, and the keying off pulses to within 5 μ s.⁹

All frequencies in the Omega system have a common epoch of 30 seconds. Thus, all RF carriers, timing pulses, and keying pulse sequences pass through zero in a positive-going direction at the same time, every 30 seconds, Omega time. The four common navigation frequencies have a common sub-epoch of about 3.53 ms, corresponding to 36 cycles at 10.2 kHz, 39 cycles at 11.05 kHz, 40 cycles at 11.33 kHz, and 48 cycles at 13.6 kHz.

4. System Operation

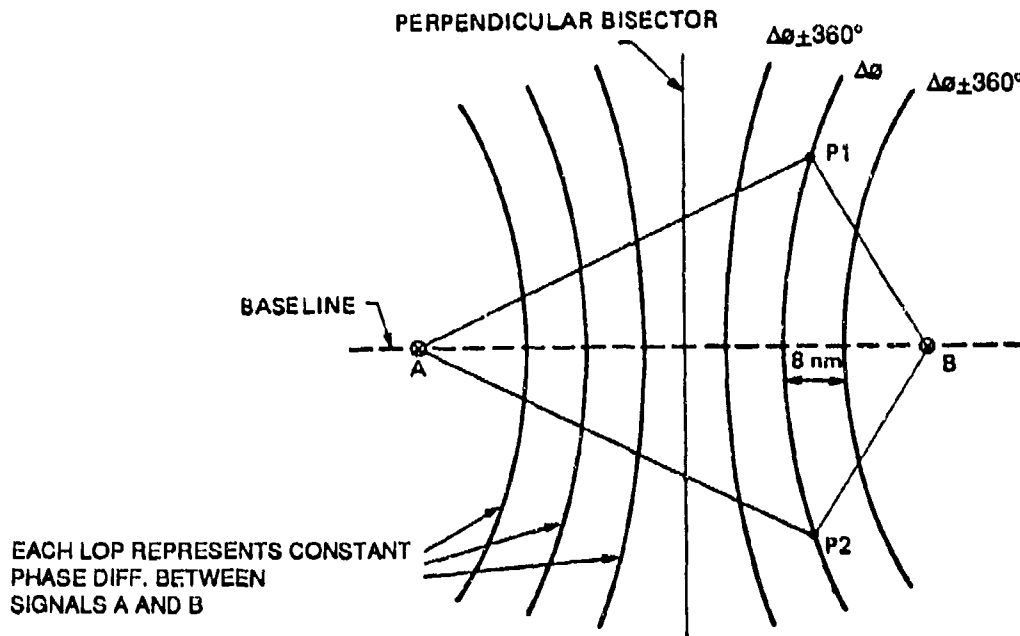
Because of the long wavelength of the Omega signal (at 10.2 kHz, the period is 98 ms and the wavelength is about 16 nmi) and the fact that it is fundamentally a CW signal, the envelope-matching and cycle-matching techniques used in Loran are neither practical nor sufficiently accurate. Instead, measurements are made of the absolute phase of a single Omega signal or of the phase difference between two Omega signals. These can be used in either a hyperbolic or a range-range mode to establish position. Both modes will be discussed below.

⁸ To adjust for changes in the earth's rotational rate, UTC is occasionally adjusted by 1 second (a Leap Second). Omega time is not adjusted to match UTC, since it might cause some Omega users to lose synchronization. As a result, on 1 July 1993, the date of the last leap second, Omega standard time was precisely 18.0 seconds ahead of UTC. The same is true for other navigation systems that rely on precise timing: As of 1 July 1993, Loran-C was also precisely 18 seconds ahead of UTC, and GPS was precisely 9 seconds ahead.

⁹ The transmitted RF pulses actually have rise times (to 63 percent of full amplitude) of as much as 20 ms, due to limited antenna bandwidth. The accuracy values given above are for the keying pulses sent to the transmitter by the timing circuits.

a. Hyperbolic Navigation

In this mode, the Omega receiver measures the phase difference between the signals received from two stations. Since the transmitters at the two stations are precisely in phase, a receiver on the perpendicular bisector of the baseline would measure zero phase difference ($\Delta\phi=0$). This is shown in Figure 19.



Source: Reference III-5

Figure 19. Hyperbolic Configuration for Omega

Other constant values of phase difference establish a set of hyperbolic LOPs. As with Loran, the navigator would measure the phase difference and thus establish his location on one of the LOPs in Figure 19. He would then measure the phase difference between the signals from another pair of Omega stations to establish another (intersecting) LOP and determine his position at the intersection of the two lines. The accuracy of this process is affected by timing errors at the transmitters, measurement errors at the receiver, atmospheric and ionospheric noise, and GDOP. The last factor, which is due to both the divergence (gradient) of the hyperbolic LOP and the non-orthogonal crossing angles, is discussed in detail in Chapter II.

b. Lane Ambiguity

If a user moves in such a direction as to cross the Omega LOPs, the measured phase of the signal from one Omega station will increase and that from the other station will decrease. The phase difference, therefore, will change at twice the rate of either of the individual phases. Thus, when the user has moved by one-half of an Omega wavelength (about 8 nmi at 10.2 kHz on the baseline between two stations), the measured phase difference will have changed by 360° , or one full cycle. This is shown schematically in Figure 19. The regions between lines of equal phase difference ($\pm 360^\circ$) are called "lanes." Since Omega receivers measure phase difference rather than absolute phase shift, a navigator using only a single measurement cannot tell which lane he is in--hence the term "lane ambiguity."

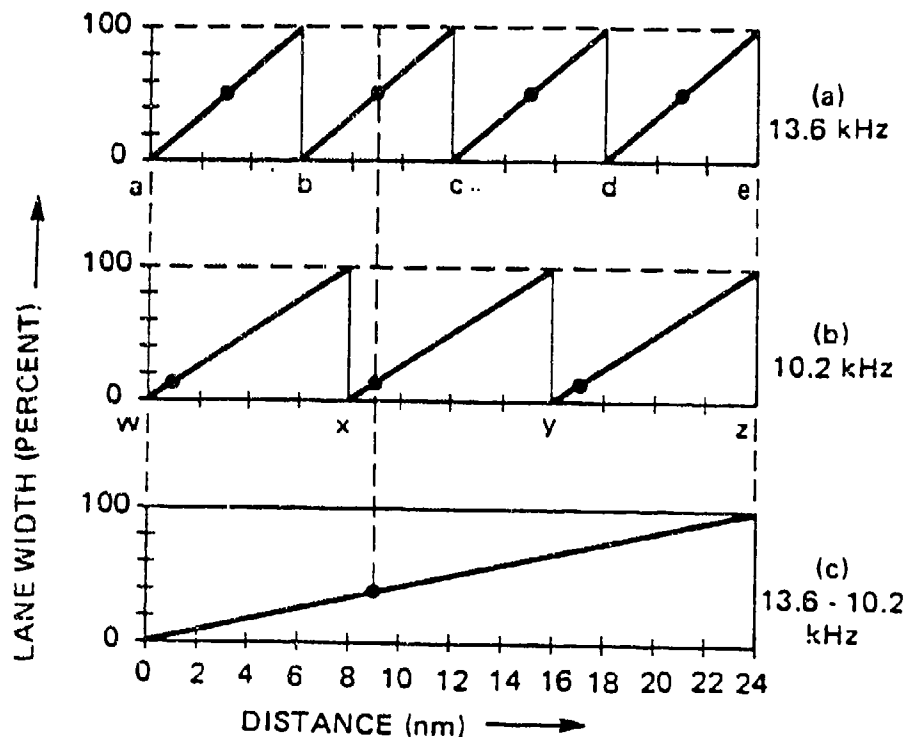
If a user started at a known position in a specified lane and counted lane boundaries (zero phase difference) as they were crossed, the identity of the current lane would always be known. Some receivers do this automatically and make the necessary corrections to determine position accurately. If, however, the lane count is lost as a result of power interruptions, atmospheric disturbances, or the inability to detect lane crossings during vehicle maneuvers, then by using only the 10.2 kHz signal, resetting the lane count requires that the receiver position be known to within ± 4 nmi.

If position information to within 4 nmi is not available, the 10.2 kHz signal can be used in conjunction with the other Omega navigation frequencies to reestablish the lane count. Consider, for example, using the 10.2 kHz and 13.6 kHz frequencies. Because of the $4/3$ ratio of the wavelengths of the two signals, there will be four 13.6 kHz lanes (6 nmi wide) for every three 10.2 kHz lanes (8 nmi wide), and the combined lane pattern will repeat every 24 nmi. This is shown in Figure 20. Note that the coincidence of the lane boundaries at the edges of the figure is not fortuitous. Due to the phasing of the signals at the transmitters, it must occur as shown, at every fourth lane of the 13.6 kHz signal.

Now assume that a measurement at 10.2 kHz gave a phase difference of 10 Cec (centicycles, or hundredths of a lane width), and that a second measurement at 13.6 kHz gave a phase difference of 50 Cec. These are plotted in Figure 20, and it is seen that only one position (in the x-y lane of the 10.2 kHz signal) will satisfy both readings. Thus, we now have an effective lane width of 24 nmi, and the user must know his position to within ± 12 nmi in order to reset the lane count. This process is called "heterodyning" since, in effect, it uses the difference frequency ($13.6 - 10.2 = 3.4$ kHz) to make the phase difference

measurements. In this example, the wavelength at 3.4 kHz is 48 nmi, and the corresponding lane width is 24 nmi, as shown in Figure 20c.

Similar measurements may be made with the other Omega frequencies. Comparing phase differences at 10.2 kHz and 11.33 kHz gives an effective lane width of 72 nmi, and comparing phase measurements at 11.05 kHz and 11.33 kHz gives an effective lane width of 288 nmi. In this last case, the position need be known only to within ± 144 nmi in order to reset the lane count.



Source: Reference III-5

Figure 20. Relative Phase Shift

c. Range-Range Navigation

If a user has an extremely accurate clock (e.g., a Cesium or Rubidium standard), he can locate himself using the following simple procedure:

- By measuring the exact time of arrival of some feature of an Omega signal (e.g., a positive-going zero crossing of the 10.2 kHz signal).

- By using knowledge of the Omega signal format to determine exactly when that signal has transmitted. Recall from the earlier discussion that major Omega epochs occur at 30-second intervals, precisely on every minute and half-minute, and that sub-epochs (when the four navigation signals simultaneously pass through zero in a positive-going direction) occur every 3.53 msec. Interpolating from these reference points will be a straightforward procedure, and there will be no lane ambiguity (the 30-second epoch is equivalent to 9×10^6 km, or about 25 times the distance from the earth to the moon).

Using the measured time difference Δt between the transmission and reception of the signal, one can establish his location or a circular LOP of radius $R = c\Delta t$, centered on the Omega transmitter, where c is the speed of light.

A similar measurement for another Omega station will establish a second circular LOP, and the user will be located at the intersection of the two circles.¹⁰ This is called range-range (or p-p) position-finding.

In actual practice, most users do not have atomic frequency standards because they represent a significant increase in the cost of an Omega receiver. Instead, they use temperature-controlled crystal oscillators that typically have a stability of 1 part in 10^8 . These oscillators will drift and, at any specified time, there will be an unknown clock bias, τ_B .

The solution to this problem is to make range measurements to three Omega stations. This give rise to the following equations:

$$\begin{aligned}\hat{R}_1 &= \left[(X_1 - x)^2 + (Y_1 - y)^2 \right]^{1/2} = c(\Delta t_1 + \tau_B) \\ \hat{R}_2 &= \left[(X_2 - x)^2 + (Y_2 - y)^2 \right]^{1/2} = c(\Delta t_2 + \tau_B) \\ \hat{R}_3 &= \left[(X_3 - x)^2 + (Y_3 - y)^2 \right]^{1/2} = c(\Delta t_3 + \tau_B)\end{aligned}\quad (\text{III-1})$$

¹⁰ There will actually be two points of intersection, but they are usually far enough apart that no confusion results. If this is not the case, a range reading from a third Omega station will be required to resolve the ambiguity.

where:

- X, Y = known locations of Omega stations
- x, y = unknown coordinates of the user's location
- Δt = measured transit times of signals
- τ_B = unknown clock bias
- c = speed of light

Thus, there are three equations in three unknowns (x, y, τ_B), and they can be solved to give both the user's position and the clock bias.¹¹ Most Omega receivers are programmed to make these calculations, and this is the most commonly used technique for position-finding with Omega.

The period of the 10.2 kHz Omega signal is 98 μ s. An oscillator stable to 1 part in 10^8 will drift 1 Cec at this frequency in about 1,090 seconds. In order to allow unambiguous correction of the clock bias, the drift should probably be kept to 15 Cec or less. Thus, readings should be made, and the clock bias corrected, every 1,500 seconds (25 minutes).

d. Hybrid Techniques

If the ranges of two Omega stations are measured, and loci plotted for which the sum of two ranges is constant, the result is a set of ellipses with the stations at the foci. If, on the other hand, loci are plotted for which the difference between the two ranges is constant, the result is a set of hyperbolae, again with the two stations at the foci. This is shown in Figure 21.

The two sets of curves are confocal and orthogonal and, since they always intersect at right angles (the definition of orthogonality), GDOP will be minimized.¹² For the user with an accurate clock (or one that has been recently corrected using the technique described in the last section), this provides an optimally simple and accurate means of determining position.

¹¹ The R_i values are called "pseudoranges" since they have not been corrected for the error resulting from clock bias.

¹² This is strictly true only if the measurement errors are random with a Gaussian zero-mean distribution. In Omega, the bias errors are the same order of magnitude as the random errors, so it can only be said that the GDOP will be reduced.

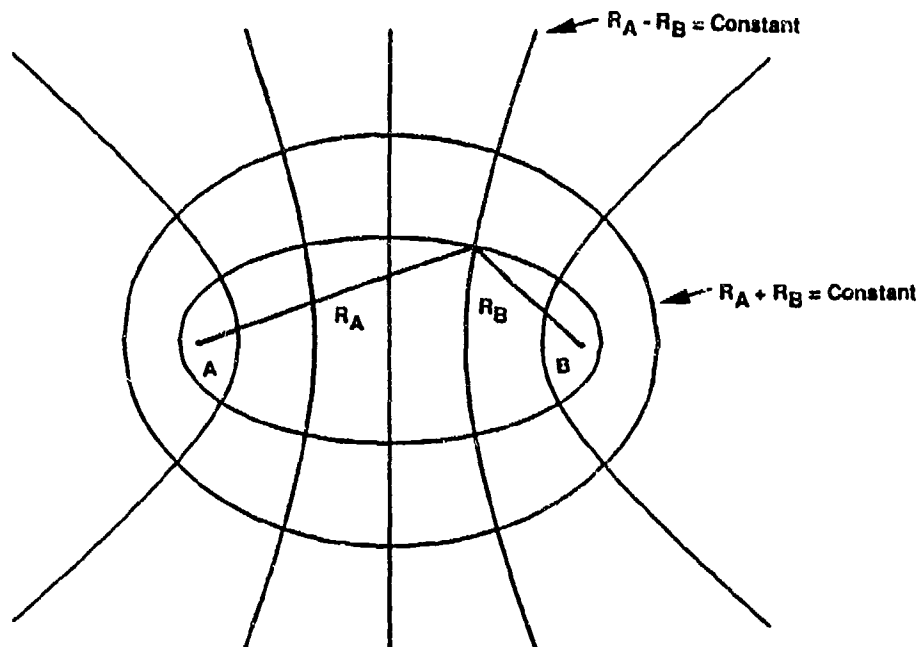


Figure 21. Orthogonal Lines of Position

As with the circles in the range-range method, the two LOPs (one ellipse and one hyperbola) used in this technique will intersect at two points. However, since Omega baselines are typically 5,000-6,000 nmi long, it can be seen from Figure 21 that the two points will generally be far enough apart to cause no confusion. If necessary, a third Omega station can be used to resolve any ambiguity.

It was noted earlier that Omega signals, particularly those traveling in an easterly direction, can propagate completely around the earth. Thus, a user can often receive a long-path signal (one that has gone more than halfway around the earth) and a short-path signal from the same station. This gives rise to another very interesting Omega navigation technique [Reference III-11]. If phase-difference measurements are made using the short-path signals from two Omega stations, the "short/short" LOPs are, as expected, a set of hyperbolae cutting the baseline between the two stations symmetrically, and curving toward the closer station. If, however, phase-difference measurements are made using the short-path signal from one station and the long-path signal from the other, the resulting "short/long" LOPs, which would be hyperbolae on a plane surface, curve back along the spherical surface of the earth and become ellipses with the two stations at the foci. The

short/short hyperbolae and the short/long ellipses are orthogonal and confocal. The geometry is the same as that shown in Figure 21, except that, in this case, the LOP are derived from phase-difference measurements rather than absolute range measurements, so it is not necessary for the receiver to have an accurate clock. Measurements made using this technique show the accuracy to be the same as that of other Omega techniques [Reference III-3].

5. Omega Accuracy and Reliability

Omega is a worldwide navigation system whose fundamental accuracy is limited by atmospheric noise, ionospheric irregularities, and phase bias. It will also vary with user location, due to geographical changes in signal strength and GDOP. The expected 2 drms¹³ values are:

Predictable	2-4 nmi	(1.8-3.6 km)
Repeatable	2-4 nmi	(1.8-3.6 km)
Relative	0.25-0.5 nmi	(450-900 m)

All Omega receivers, whether manual or automatic, must apply a correction for the propagation delay from each station resulting from diurnal and seasonal variations of the ionosphere. Data to derive these propagation corrections are gathered at 54 Omega monitor station located at surveyed sites around the world. Correction values are calculated by the Omega Navigation System Operations Detail of the U.S. Coast Guard and are published as Propagation Correction Tables by the Defense Mapping Agency. Navigation charts overprinted with the Omega grid lattice are also available.

Availability of individual Omega stations is better than 99 percent. Joint availability of three stations exceeds 97 percent, including both emergency shutdowns and scheduled off-air maintenance periods.

¹³ Defined as the radius of a circle containing 95 percent of the position fixes.

6. Differential Omega

Improved accuracy can be realized by locating an Omega receiver at a surveyed site, comparing the phases of the received Omega signals with those expected at its known location, and broadcasting correction factors to users in its service area. Accuracies of 0.25 nmi (450 m) can be expected within 50 nmi of the monitor station, gradually deteriorating to 1 nmi at 500 nmi from the station.

The Omega corrections are broadcast by adding a 20 Hz modulation signal to the carrier of a radiobeacon station. At present, there are 14 operational Differential Omega stations and 3 planned ones. Those are shown in Figure 22. Note that seven of those provide overlapping coverage of Central Europe. Combining (averaging) the phase corrections from those stations should provide accuracy over the area to 300 m or better.

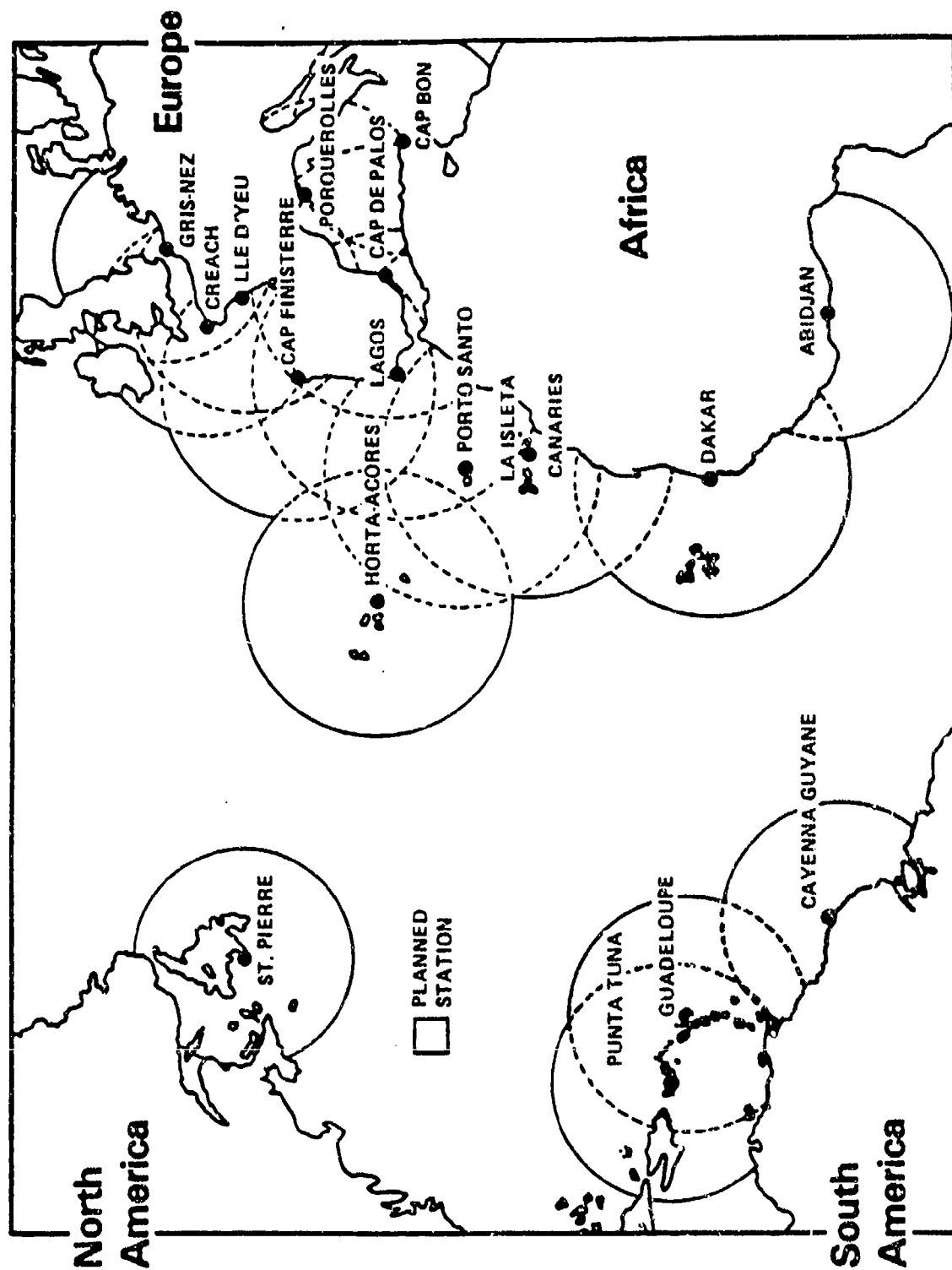


Figure 22. Differential Omega Coverage

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IV. TRANSIT

Transit, the Navy navigation satellite system, has a very interesting history that includes elements of synergism, technical innovation, and even national pride. When the Soviet Union launched Sputnik I, the first earth-orbiting satellite, in October 1957 the American reaction, especially among the scientific community, was one of shock, amazement, and fear. Our reputation seemed to be at stake, and the result was a space race between the two superpowers lasting nearly 15 years. In January 1958, the United States launched Explorer I, its first earth-orbiting satellite. The Soviets put the first man in space in April 1961; the United States followed suit in May 1961, in the first of a long series of flights that culminated with a landing on the moon in July 1969. A brief summary of the highlights of the programs is given in Table 7.

Table 7. U.S. and Soviet Space Flights

Date	Name	Nation	Remarks
4 Oct 57	Sputnik 1	USSR	First artificial satellite
31 Jan 58	Explorer 1	US	
12 Sept 59	Luna 2	USSR	First spacecraft on moon
12 Apr 61	Vostok 1	USSR	First manned spaceflight (Gagarin)
5 May 61	Freedom 7	US	Suborbital flight (Shepard)
29 Jun 61	Transit 4A	US	First navigation satellite
20 Feb 62	Friendship 7	US	First American in orbit (Glenn)
27 Aug 62	Mariner 2	US	Geophysical studies of Venus
Jan 64	Transit	US	First fully operational satellite
28 July 64	Ranger 7	US	Moon impact
28 Nov 64	Mariner 4	US	Mars probe
12 Nov 65	Venera 2	USSR	Venus probe
16 Nov 65	Venera 3	USSR	Venus probe
31 July 66	Luna 9	USSR	Soft landing on moon
30 May 66	Surveyor 1	US	Soft landing on moon
12 Jun 67	Venera 4	USSR	Soft landing on Venus
16 July 69	Apollo 11	US	First moon landing (Armstrong, Aldrin)

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The concept for Transit was born shortly after the launch of Sputnik I in 1957, when Dr. William H. Guier and Dr. George C. Weiffenbach at the Applied Physics Laboratory of Johns Hopkins discovered that they could determine the orbit of the satellite very accurately by knowing their own location on the ground and measuring the Doppler frequency shift of the 20 MHz radio signals from the satellite. The entire orbit could be determined from the Doppler data gathered during a single satellite pass. Although it seems surprising that this could be accomplished by a few measurements made from a single ground site it was, as pointed out by Stansell [Ref. IV-8], "because of a concept termed Dynamic Geodesy. Simply stated, a satellite is not free. It is trapped in the earth's gravity field. Therefore, by mathematically accounting for the gravity constraints imposed on any possible satellite orbit, only one specific orbit could both satisfy the laws of physics and account for the measured Doppler curve."

It was quickly realized that the inverse would also be true: if a satellite's orbit were known, a user on the ground could determine his own location by making measurements of the Doppler shift of a radio signal from the satellite. Transit, the Doppler navigation satellite system, had been conceived.

The rapid development of Transit was encouraged by two factors: The first was the impetus of the space race, which has already been discussed, and the second was the fact that the Navy was looking for a passive navigation system for its Polaris program--one that would allow the submarines to determine their position without having to radiate a signal. Continuous operation was not required, since the primary purpose of these fixes would be to update the onboard Ships Inertial Navigation System (SINS). Initial funding for the program was provided by the Navy in December 1958, and the first experimental satellite (Transit 1A) was launched 10 months later in September 1959. It failed to achieve orbit because of a failure of the Thor Able launch vehicle, but its backup (Transit 1B) was placed in orbit in April 1960. Following a series of experimental satellites, the first operational Transit satellite was launched in December 1963 and activated in January 1964. The Transit system has been continually operational since that time. The first complete five-satellite Transit constellation was launched from April 1967 to August 1970.

A. THE TRANSIT SYSTEM--A TECHNICAL DESCRIPTION

A detailed technical description of the proposed Transit system was given in a 1960 paper by Guier and Weiffenbach [Ref. IV-2] in which they provided the rationale for many of the parameters of the system:

- A single satellite in a circular polar orbit at an altitude of 400 nmi will provide a user anywhere on earth with the opportunity for a navigation fix at least twice a day. The number of satellites determines the number of opportunities for fixes. Since the system was intended for Polaris submarines, which did not need continuous position-finding (especially since they had to come to periscope depth and extend an antenna above the sea surface in order to use Transit), a constellation of four satellites would be adequate. This would provide an interval between fixes of about 1.5 hours over most of the earth's surface.
- The satellite altitude should be high enough to avoid the perturbation caused by atmospheric drag. However, increasing the altitude not only decreases the signal strength seen by a user on the ground but also decreases the Doppler shift and reduces the accuracy of the navigational fix. Altitudes between 400 and 500 nmi were felt to be about optimum.
- The satellites should transmit two stable CW frequencies. The stability should be such that the frequencies are essentially constant during a satellite pass (1 part in 10^8 is sufficient), and two frequencies are required so that a real-time correction for ionospheric refraction can be made. Finally, the frequencies should be within the range of the transistor oscillators and amplifiers which were available in 1960. Frequencies in the 200-400 MHz region were recommended.
- Satellite transmitter powers of 100 milliwatts (mW) would give adequate signal strength at the earth's surface, even for receivers with simple antennas.

Table 8 shows that the operational Transit system is remarkably similar to the one proposed by Guier and Weiffenbach:

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Table 8. Parameters of Transit System

Number of Satellites	7
Orbits	Type: Circular Polar Altitude: 1,075 km (580 nmi) Period: 107 min
Carrier Frequencies	150, 400 MHz ^a
Navigation Message	Length: 2 minutes Contents: Ephemerides, Time Marks
Clock Stability	1 part in 10 ¹¹
Satellite Weight	135 pounds
Satellite Size ^b	12 x 18 inches

^a These are the receiver frequencies. The satellite frequencies are offset to 399.968 and 149.968 MHz, for reasons to be discussed later.

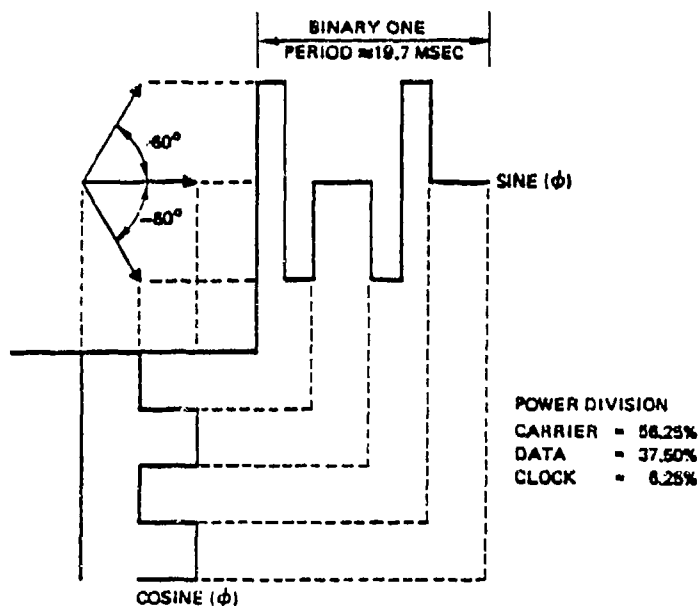
^b Core size, not including solar panels and gravity gradient stabilizer arm.

The Transit system consists of three separate segments:

- The user equipment, which includes the Transit receiver, a navigation computer, and the necessary interfaces with other navigation systems on the user platform (Loran, inertial, Omega, gyrocompass, etc.).
- The satellite constellation, which now consists of seven operational satellites and six on-orbit spares. If all of the orbits were equally spaced, this would provide a time between fixes of less than 70 minutes at the equator and less than 30 minutes at a latitude of 70°. Unfortunately, the orbits have not precessed uniformly and are no longer evenly spaced. Occasionally (less than 5 percent of the time), the delay between fixes can be as much as 5 hours.
- The ground monitoring system, which includes tracking stations in Maine, Minnesota, Hawaii, and California, and the control center at Point Mugu, California. These stations measure the Doppler frequency of each satellite as it passes and forward the data to Point Mugu where precise orbits are calculated. Corrected orbital parameters, extrapolated 16 hours into the future, are uploaded to each satellite every 12 hours.

B. THE NAVIGATION MESSAGE

The transit navigation message is 2 minutes long, starts on every even minute, and contains 6,103 bits. The data are transmitted by phase modulation of both the 150 and 400 MHz carriers, using the format shown in Figure 23,¹ which also serves to provide a clock signal at twice the data rate.



Source: Reference IV-9

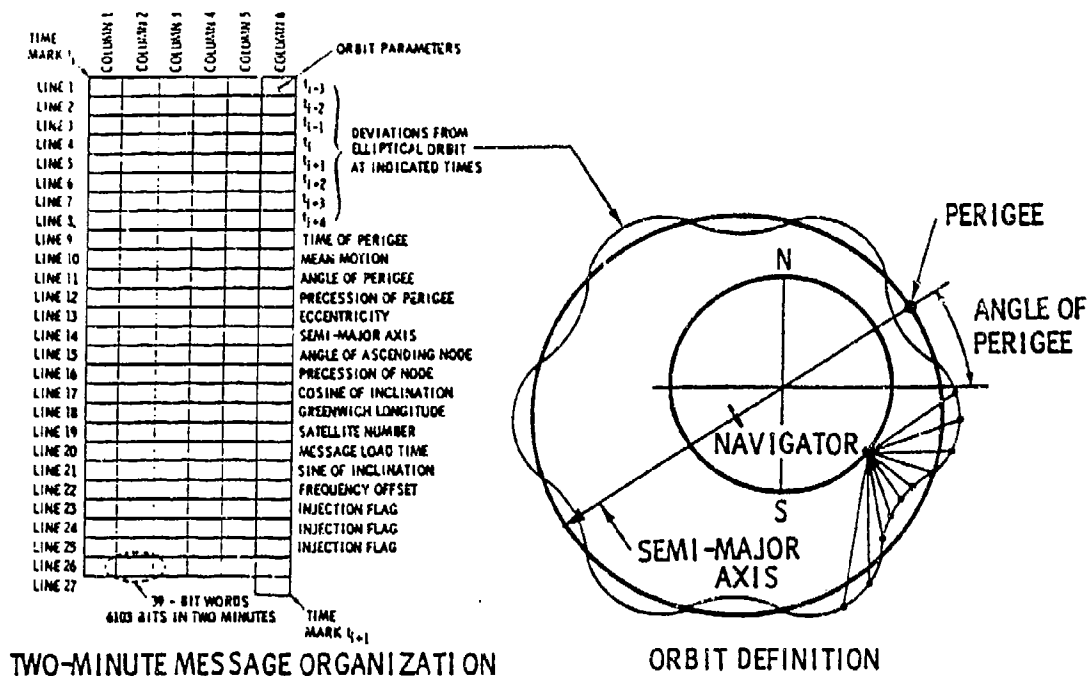
Figure 23. Transit Data Phase Modulation

The format of the message is shown in Figure 24. It consists of a total of 156 39-bit words arranged in 6 columns and 27 lines, with a closing 19-bit end-of-message (time mark) word.

The satellite orbital data are given in two parts: A set of fixed parameters (lines 9 through 22), which describe a smooth, precessing, elliptical orbit; and a set of variable parameters (lines 1 through 8), which describe the deviation of the actual orbit from the

¹ The pattern shown is for a binary one. The binary zero uses the inverse of this pattern.

ideal smooth ellipse (see Figure 24). The fixed parameters are changed only rarely when the ground control station determines that the satellite orbit has moved enough to warrant it.

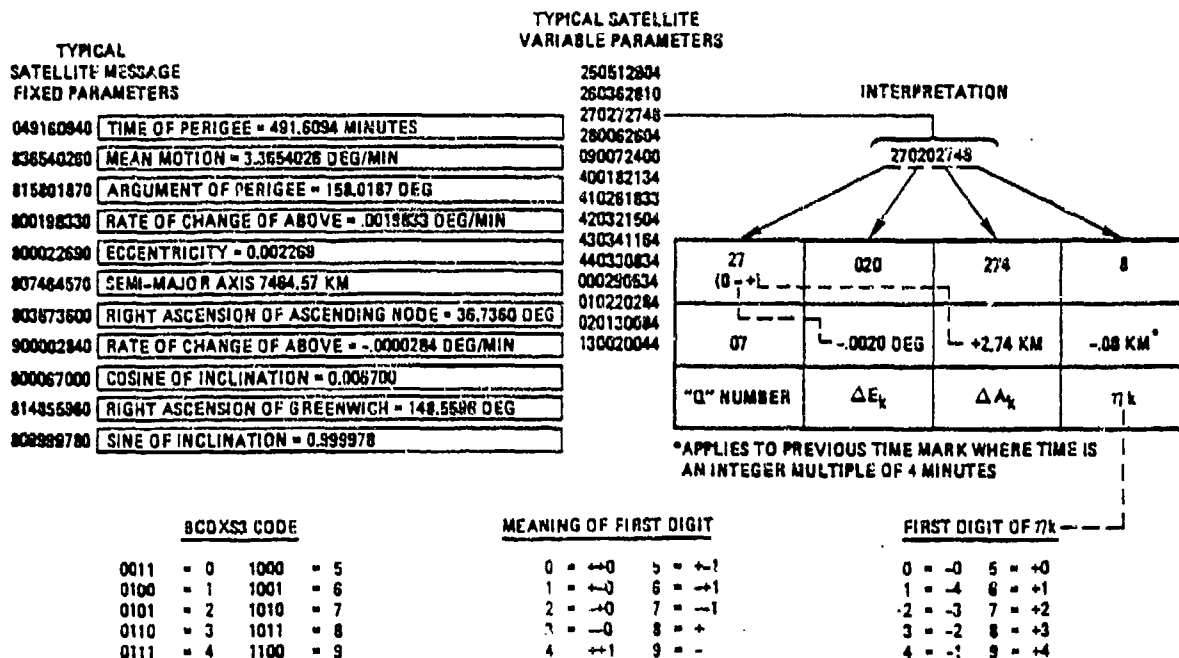


Source: Reference IV-9

Figure 24. Transit Navigation Message

The variable parameters in lines 1 through 8 move up one line every 2 minutes, with a new word added at line 8, and the word at line 1 discarded. The variable parameters are stored in satellite memory and are updated by the ground control stations every 12 hours.

The first five columns of the navigation message are used by each satellite to send the fixed orbit parameters of the other satellites in the Transit constellation. The space normally occupied by the variable parameters is used to send administrative data (satellite health, error messages, etc.), and to send operational messages to the Polaris submarines. Column six is used to send the satellite's own orbital data. A typical message is shown in Figure 25.



Source: Reference IV-9

Figure 25. Interpretation of the Transit Message Parameters

The fixed parameters shown at the left of the figure are the classical Kepler orbital equation parameters for an earth-centered, earth-fixed coordinate system.² As noted earlier, these parameters define nominal, smooth elliptical orbits for all of the satellites in the Transit constellation.

Eight separate sets of variable parameters are sent in lines 1-8 of column six. One set is valid as of the starting time (t_i) of the current navigation message, three are valid at 2-minute intervals in the past ($t_i - 1, 2, 3$), and four are valid at 2-minute intervals in the future ($t_i + 1, 2, 3, 4$). These parameters give the actual satellite position in terms of deviations from the nominal ellipse defined by the fixed parameters. The format is shown at the right in Figure 25:

- The "Q" number is a tag that gives the time in 2-minute intervals, starting each half hour. The number 07 in the example means that this particular navigation

² For a detailed discussion of the definitions of both the fixed and variable parameters, see Stansell, Reference IV-9.

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message started at either 14 or 44 minutes past the hour. The fact that the "Q" number spans a half hour means that a new user must have his clock set to within 15 minutes of Transit time (GMT) in order to synchronize properly.

- The other three terms specify a set of orthogonal corrections to the satellite position: ΔA gives the error in the direction of the semi-major axis of the ellipse, ΔE gives the error in the eccentricity, and η gives the error normal to the plane of the ellipse. When used as corrections to the fixed parameters, these terms, in effect, define a new ellipse that passes through the satellite at its present location. By interpolating among the variable parameters, it is possible to find the satellite position at any point in its orbit.

A user receiving the navigation message can perform several critical steps in the navigation process:

- He can set his clock to Transit time, first by using the "Q" number, next by using the time marks at the beginning and end of each message, and finally by using the synchronization signals inherent to the modulation format.
- By using both the fixed and variable parameters, he can establish the orbit of the active satellite very accurately.
- He can determine the nominal orbits of the other Transit satellites and decide when another one will become visible for a subsequent position fix.

C. THE DOPPLER MEASUREMENT

The other worldwide navigation systems (Loran, Omega, and GPS) rely for their operation on the measurement of propagation times or time differences. Although some of the details are complex, the basic concepts of these systems are intuitively quite simple.

Transit, on the other hand, relies on Doppler frequency shifts caused by motion of a satellite relative to the user. Since the process now involves measuring relative velocity rather than relative position, the measurement technique is somewhat more complicated and, therefore, will be explained in detail. The geometry is shown in Figure 26.

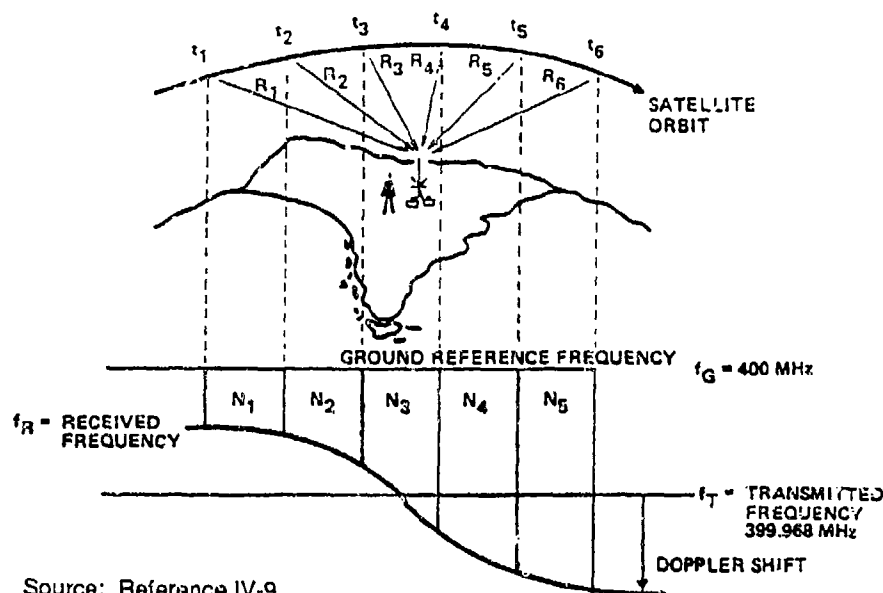


Figure 26. Doppler Count Measurement

As shown in the figure, the slant range, R , from the satellite to the user changes as the satellite moves along its orbit. It is, in fact, this changing range that causes the Doppler shift: as the satellite moves closer (R decreases), the received frequency will increase, and as it moves further away (R increases), the received frequency will decrease. The Doppler shift is the difference between the transmitted and received frequencies ($f_T - f_R$) and, as indicated in the figure, it changes during the satellite pass. The variable actually measured by the receiver is $(f_G - f_R)$ where f_G is the ground reference frequency of 400 MHz. Note that, as mentioned earlier, the satellite transmitter frequency is offset by 32 kHz so that the measured quantity $(f_G - f_R)$ will always be positive. An inspection of Figure 26 will make this clear.³

A signal transmitted by the satellite at time t_1 will be received at time $t_1 + R_1/c$, where R_1 is the slant range and c is the speed of light. Similarly, a signal transmitted at time t_2 will be received at time $t_2 + R_2/c$. Thus the total Doppler frequency count during the interval t_1 to t_2 is given by

³ This procedure adds a constant 32 kHz to the measured Doppler frequency. It will be seen later that this constant offset makes no difference in the final result.

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$$N_1 = \int_{t_1 + R_1/c}^{t_2 + R_2/c} (f_G - f_R) dt \quad (IV-1)$$

$$= \int_{t_1 + R_1/c}^{t_2 + R_2/c} f_G dt - \int_{t_1 + R_1/c}^{t_2 + R_2/c} f_R dt \quad (IV-2)$$

The first integral is easily evaluated, since f_G is a constant. The second is treated by invoking what Stansell [Ref. IV-9] calls "the law of conservation of cycles": The number of cycles transmitted by the satellite between two given timing marks must equal the number of cycles received by the ground station between the same two timing marks. As the satellite moves toward the user, the frequency of the signal will increase, the wavelength will decrease, and the interval between the timing marks will decrease, but the total number of cycles will remain the same. The converse is true when the satellite is moving away from the user. Equation IV-2 thus becomes

$$N_1 = \int_{t_1 + R_1/c}^{t_2 + R_2/c} f_G dt - \int_{t_1}^{t_2} f_T dt \quad (IV-3)$$

$$= f_G \left[(t_2 - t_1) + \frac{1}{c} (R_2 - R_1) \right] - f_T (t_2 - t_1) \quad (IV-4)$$

$$= (f_G - f_T)(t_2 - t_1) + \frac{f_G}{c} (R_2 - R_1) \quad (IV-5)$$

The first term is a constant resulting from the offset between the satellite frequency (f_T) and the ground reference frequency (f_G), and the second term is a direct measure of the change in the slant range during the measurement interval. Rearranging equation IV-5 gives

$$\Delta R = R_2 - R_1 = \lambda_G [N_1 - \Delta F \Delta T] \quad (IV-6)$$

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where: $\lambda_G = c/f_G$ = Wavelength of Ground Reference Frequency (= 0.75m)

$\Delta F = f_G - f_T$ = Frequency Offset (= 32kHz)

$\Delta T = t_2 - t_1$ = Time Interval

Finally, note that the total cycle count N_1 is composed of two parts: a constant term ($\Delta F \Delta T$) due to the frequency offset (which will always be positive), and the actual integrated Doppler cycle count (N_{D1}) for the period (which may be either positive or negative). We then have

$$\Delta R = \lambda_G N_{D1} \quad (\text{IV-7})$$

where: N_{D1} = Integrated Doppler cycle count for period $t_2 - t_1$.

and the Doppler cycle count is seen to be directly proportional to the change in slant range.⁴ Each time the slant range changes by one wavelength ($\lambda_G = 0.75\text{m}$), the Doppler count changes by one cycle. This provides a very sensitive measure of the change in the slant range.

D. POSITION LOCATION USING TRANSIT

The user now has everything he needs: an accurate reference to Transit clock time, data from which the orbit of the satellite can be accurately calculated, and the Doppler cycle counts, which uniquely determine his own location.

A satellite will be visible above the horizon for about 11 minutes if it passes directly overhead, and for almost 20 minutes if it is near the horizon. During this time, the Transit receiver will measure the Doppler count for each of several successive segments of the satellite orbit.⁵ Measurement of the length of these segments is usually referenced to timing marks in the navigation message, so as to minimize the requirement for user clock accuracy. For example, one could use the length of the entire navigation message to establish a measurement interval of 2 minutes, or establish an interval of just over 23 seconds by starting a new count at the beginning of every fifth line of the message.

⁴ This actually follows directly from the "law of conservation of cycles."

⁵ Each of those measurements is, as stated by Guier and Weiffenbach in their original paper [Ref. IV-2], "more or less statistically independent."

The satellite signal is delayed by interaction with free electrons and ions in both the troposphere and the ionosphere. This results in an increase in the apparent wavelength of the signal and, therefore, an increase in the measured slant range from the satellite to the user. Since the satellites move in generally north-south orbits, the resultant position-finding errors are primarily in longitude. The delays in both the troposphere and ionosphere are dispersive (i.e., frequency dependent).

- The troposphere error is relatively small and is easily corrected by computer models based on the atmospheric temperature, pressure, and relative humidity. It is also helpful to avoid measurements when the satellite is near the horizon, where the path length is longest and the troposphere errors are greatest. For measurements taken at elevation angles of 20° or more, the uncorrected troposphere error will be less than 8 meters (rms). The corrected error will be less than 1 meter (rms).
- The ionospheric time delay depends on the local ionization level which, in turn, varies both seasonably and diurnally, and is a function of the sunspot cycle, as well as the location with respect to the magnetic equator. It is not easily predicted. However, the time delay (and the apparent increase in the wavelength) is, to a very good approximation, inversely proportional to the square of the carrier frequency. Thus, for any system, such as Transit, which transmits on two separate frequencies, it is easy to show that

$$\Delta\tau = \tau_2 - \tau_1 = \tau_1 \left[\left(\frac{f_1}{f_2} \right)^2 - 1 \right] \quad (\text{IV-8})$$

where: f_1, f_2 = Carrier frequencies (150 and 400 MHz)

τ_1, τ_2 = Corresponding time delays.

Thus by measuring the difference in the time delay ($\Delta\tau$) between the two signals, and knowing the two carrier frequencies, the absolute time delays (τ_1, τ_2) are easily calculated. The error in the users position due to uncorrected ionospheric time delay errors can be 500 meters or more. When corrected, the error will be less than 5 meters.

The actual computation of the user's position is based on a series of successive approximations. As noted earlier, the user receiver measures the Doppler count for a series of segments of the satellite pass, and it also calculates the satellite's position at the beginning and end of each segment. The user enters his best estimate of his current position in three dimensions (latitude, longitude, and altitude). Since the measurements are

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made according to equation IV-6, and since both the satellite and the receiver are using crystal oscillators, the frequency offset ($\Delta F = f_G - f_R$) is also treated as an unknown,⁶ and a best estimate is entered. Based on these estimated values and the known positions of the satellite at the beginning and end of the segment, a slant range change is calculated and this is compared with the measured slant range change given by equation IV-6. The residual error between the calculated and measured values is due to errors in the estimated values of latitude (ϕ) longitude (λ) and frequency offset (ΔF). The purpose of the ensuing calculations is to find values of these parameters that minimize the residual error.⁷ New values of λ , ϕ , and ΔF are chosen, a new value of the error is calculated, and this process is iterated until the error is reduced to some acceptable value. A number of mathematical techniques are available to help with this process (Kalman filtering, estimation theory, steepest descent algorithms, etc.⁸) In practice, it is found that the solution converges very rapidly, and that only a few iterations are required even if the original position estimate is off by several tens of kilometers.

E. TRANSIT ERROR SOURCES

A number of potential error sources must be considered. Some are common to all position finding systems, some are shared by all satellite systems, and some are peculiar to Transit.

- **Propagation Delays.** It was noted earlier that unknown time delays in the troposphere and ionosphere can lead to position errors of 500 meters or more. These can be corrected, and the error reduced to 5 meters or less.
- **Orbit Errors.** The prediction of the satellite orbit is limited by the accuracy to which the earth's gravity field is known. This has improved over the years, based on actual measurements of the Transit (and GPS) satellites themselves, but is still a source of error. Also, the extrapolated Transit orbital parameters that are included in the navigation message may be in error as a result of unexpected changes in the satellite orbit caused by solar wind or radiation pressure.

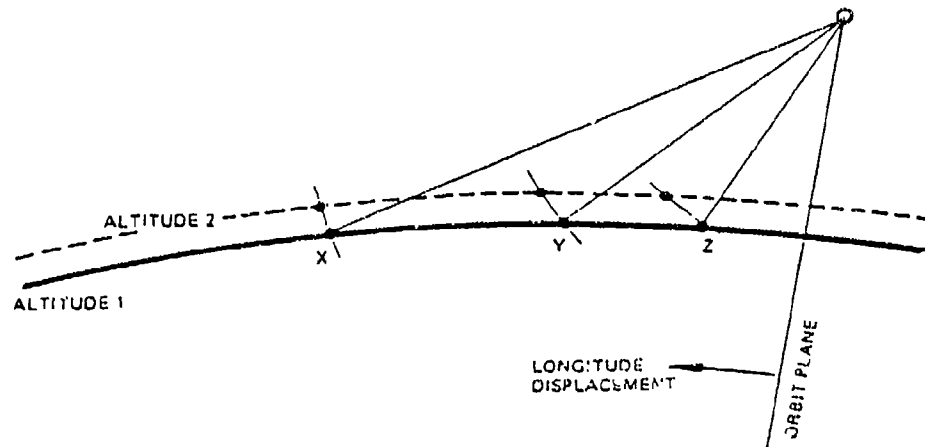
⁶ If they both had atomic clocks, ΔF would be known, and equation IV-7 could be used instead.

⁷ ϕ , λ , and ΔF are orthogonal, so their errors can be minimized independently, and a global (absolute) minimum can be found.

⁸ A relatively simple one, which minimizes the mean-squared error based on linear combination of first-order terms, is described in Reference IV-9, Section 5.4.

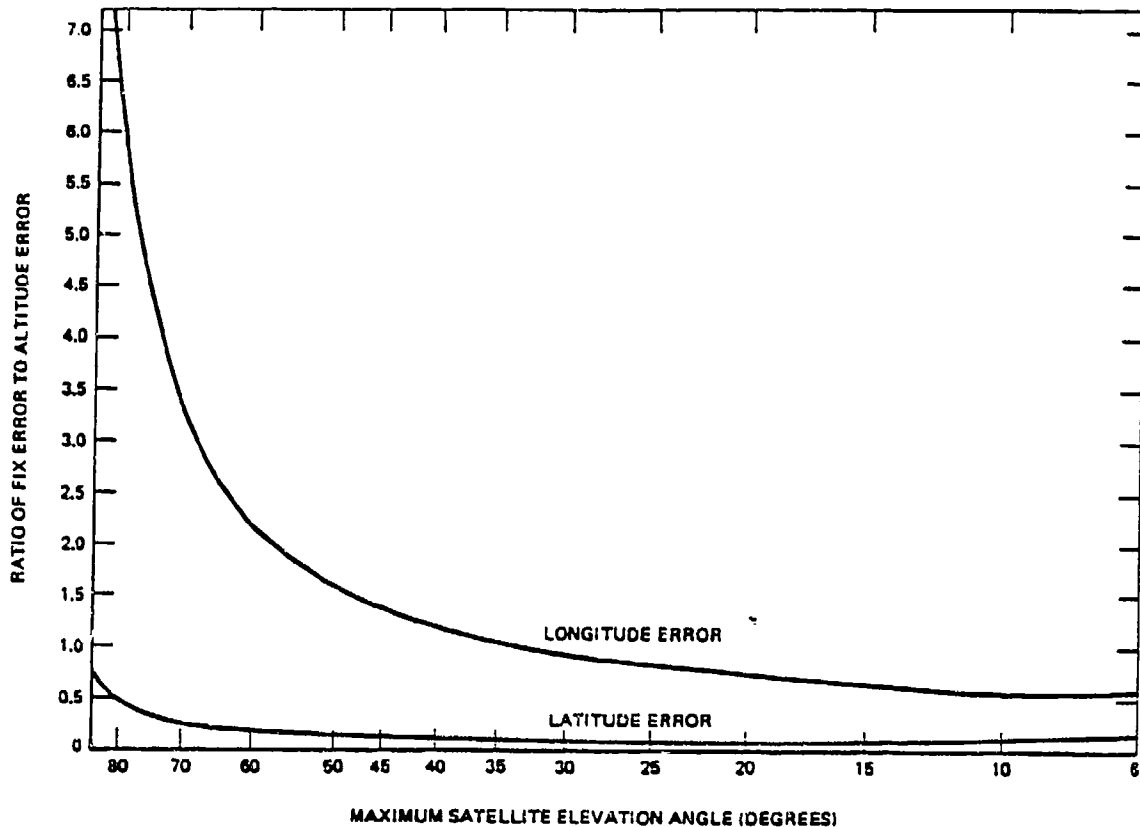
- **User Altitude.** Since Transit depends for its operation on a measurement of the slant range between the satellite and the user, the estimate of the user altitude (specifically, the altitude to the antenna) is quite important. The geometry of the problem is shown in Figure 27a where the satellite is moving out of the page, and the measured longitude is seen to depend strongly on the estimated altitude. It is also seen that the magnitude of the error increases as the elevation angle to the satellite increases. The magnitude of the error is shown in Figure 27b. Since the satellites are in polar orbits, moving in a north-south direction, the error is primarily in longitude.

The situation is further complicated by the fact that altitude is normally measured with reference to the local reference ellipsoid. The true altitude, however, is with respect to the local mean sea level, which is the true geoid. The difference between the two may be as much as 100 meters, and this must be taken into account.



Source: Reference IV-9

Figure 27a. Effect of Altitude Estimate on Position Fix

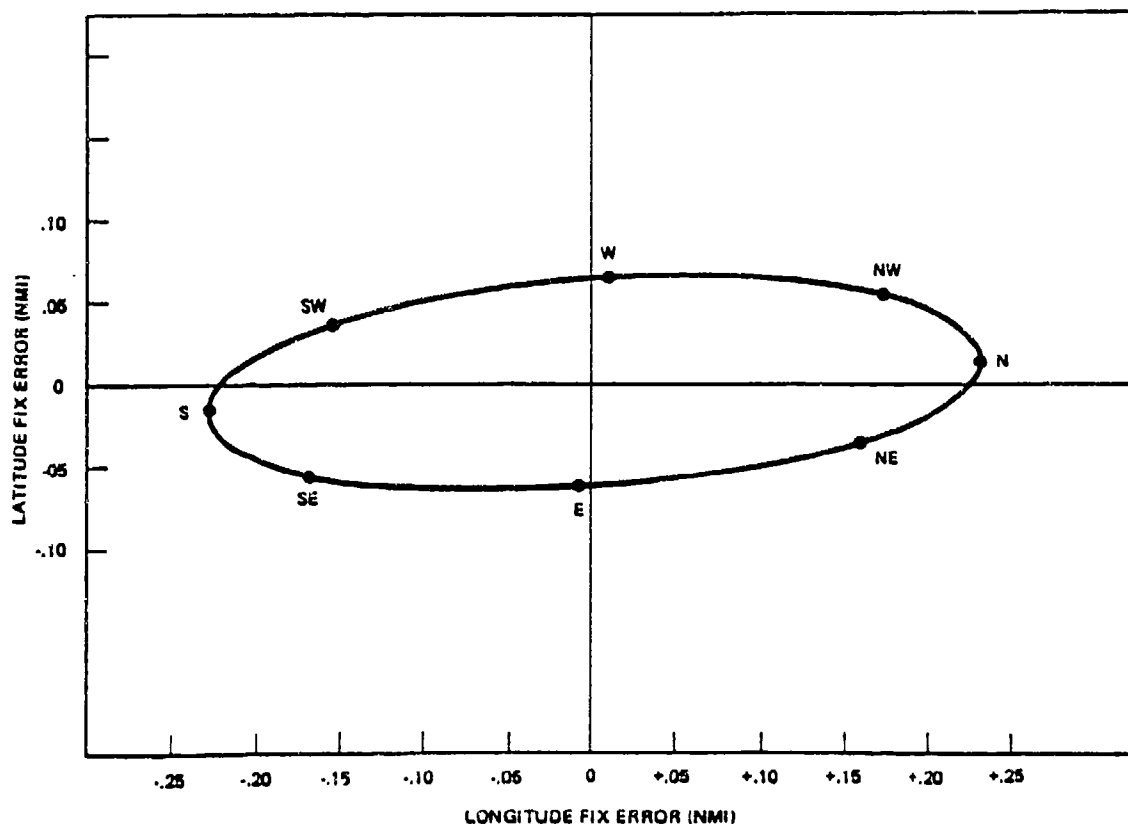


Source: Reference IV-9

Figure 27b. Sensitivity of Satellite Fix to Altitude Estimate Error

- **User Velocity.** Transit measurements are made over a period of 10-20 minutes, and the accuracy of the final position fix depends upon how well the user's location can be estimated during this time (see Section D). For a stationary receiver, this is no problem, and for moving receivers, it is no problem so long as the velocity is precisely known.⁹ In other cases, the position fix error is a function of the velocity error (both magnitude and direction), the satellite elevation, the location of the satellite (east or west) relative to the user, and whether the satellite is moving south or north. Figure 28 shows the position fix error resulting from a one-knot velocity error in each of the eight cardinal compass directions, for a satellite at an elevation angle of 31°, located east of the user, and moving north.

⁹ The rotation of the earth imparts a velocity of more than 5,200 km/hr to a user at the equator. This causes no problem because it is precisely known. Errors are caused only by unknown velocities.



Source: Reference IV-9

Figure 28. Effect of a 1-Knot Velocity Error on the Position Fix

The direction of the velocity error is shown beside each of the data points. Note that the errors are primarily in longitude and that they can be as much as 0.25 nmi for this 1-knot error. The errors increase with increasing elevation angle and can be as much as 0.75 nmi for an elevation angle of 80° . This dependence on velocity errors limits the utility of Transit for aircraft, missiles, and other high dynamic vehicles.

The error budget for a fixed or slowly moving user is summarized in Table 9 below.

The root sum square (rss) error under normal operating conditions is seen to lie between 19 and 28 meters, which is truly remarkable for a simple one-satellite navigation system.

Transit has no lane ambiguities such as those of Omega. The only anomaly results from the fact that the slant range (Doppler) changes are the same for two points equidistantly spaced on either side of the satellite orbit. However, the velocity imparted to

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the user by the earth's rotation will be toward the satellite at one of the points and away from it at the other. As a result, the iterative solution for the fix will converge very slowly, if at all, at the incorrect location.

Table 9. Transit System Errors

Source	Error (meters)
Unresolved propagation effects (ionosphere and tropospheric)	1-5
Instrumentation and measurement noise	3-6
Orbit errors	15-25
Altitude uncertainties	10
Ephemeris rounding error (last digit is rounded)	5
	<hr/> 19-28 m (rss)

F. TRANSIT PERFORMANCE

The Federal Radionavigation Plan gives the single-pass accuracy of Transit as 25 meters and the repeatable accuracy as 15 meters. It also notes that the coverage is worldwide (although not continuous), and that the reliability is 99 + percent.

Three other applications of Transit should be noted:

- **Surveying.** By observing multiple passes of Transit satellites, it is possible to improve the accuracy and, at the same time, to determine the location in three dimensions (latitude, longitude, and altitude).¹⁰ Experimental data show maximum three-dimensional errors of 7 meters (rss) after 10 satellite passes, and 5 meters after 25 passes.
- **Translocation.** When two receivers make measurements on the same satellite, most of the errors are strongly correlated, even for separations of 200 km or more. Thus it is possible to locate two or more stations with respect to each other with great accuracy. It has been shown that, using four satellite passes, relative locations can be determined with an accuracy of one meter or less.
- **Differential Transit.** In this mode of operation, a Transit station is placed at a known surveyed location. It measures its own location using Transit,

¹⁰ Determining the altitude requires measurements from satellites at different elevation angles.

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compares that with its known position, calculates the fixed (bias) errors for the satellite, and broadcasts these corrections to other users in the area. They are then used to correct the user's measured Transit fixes.¹¹ The differential accuracy will be about the same as for translocation (1 meter rss), except that the differential mode gives absolute position, while translocation gives only relative position.

¹¹ The other major navigation systems (Loran, Omega, and GPS) can also use differential position-fixing. In each case, the accuracy is improved by at least a factor of 10.

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V. GLOBAL POSITIONING SYSTEM (GPS)

While Transit was being developed and tested, there were two other active navigation satellite programs: the Navy Timation system and the Air Force System 621B. They differed in concept, but had much in common. Timation, for example, would have a constellation of 27 satellites in polar orbiting planes with 8-hour periods. Each satellite would transmit ranging signals on two frequencies and would provide the users with timing signals and satellite ephemeris data. 621B, by contrast, would have several constellations of geosynchronous satellites transmitting navigation data by way of a pseudo-randomly modulated spread-spectrum signal that would provide both a timing reference and jamming protection.

But while Transit based its operation on measuring the Doppler shift of the satellite signals, both Timation and 621B relied on accurate synchronization of clocks on the satellites and in the user's receiver. With this, it would be possible to measure the transit time of the radio signal (and thus the range) from the satellite to the user. One measurement would provide a circular line of position on the surface of the earth, and three would provide an accurate three-dimensional position fix. The concept would give several advantages over Transit: three-dimensional fixes would be possible; both user position and user velocity (using Doppler measurements) could be determined, and the process would be essentially instantaneous so that motion of the user platform would not be a problem.

The first satellite, Timation I, was launched in May 1967 and used a quartz oscillator with an accuracy of 3 parts in 10^{11} per day. The oscillator on Timation II, which was launched in September 1969, had an accuracy of 1 part in 10^{11} per day. These were to be followed by satellites using atomic frequency standards (1 part in 10^{13} per day) as soon as they became rugged and reliable enough.

In 1973, the Department of Defense merged the Navy Timation and the Air Force 621B program into a single Navigation Technology Program, and this became the basis for the current GPS system. The first satellite under the new program, called Navigation Technology Satellite One (NTS-1) was launched in July 1974 with two Rubidium clocks accurate to 1 part in 10^{12} per day. NTS-2 was launched in July 1977 with two Cesium clocks accurate to better than 2 parts in 10^{13} per day.

A. SYSTEM DESCRIPTION

GPS is a space-based navigation, position finding, and time distribution system that will provide precise, continuous, all-weather, common-grid, worldwide navigation and timing to air, land, sea, and space-based users. GPS consists of three segments:

- The **Space Segment**, which is shown schematically in Figure 29, consists of 24 operational satellites in 20,000-km, 12-hour orbits, evenly spaced in 6 orbital planes. This provides visibility of 6-11 satellites at 5° or more above the horizon to users located anywhere in the world at any time.
- The **Control Segment** consists of a single Master Control Station and a set of monitor stations at widely separated locations around the world. The monitor stations passively track all satellites and accumulate ranging data from the navigation signals. This information is sent to the Master Control Station where it is processed to determine precise satellite orbits and to identify systematic errors. The Master Control Station uploads the satellite ephemerides, clock drift corrections, and propagation delay data to the satellites as required.
- The **User Segment**. Using a receiver with one or more channels, the user measures the apparent ranges to four satellites and can then calculate his three-dimensional position and accurate time.¹ Measurement of the Doppler shift of the satellite signals also allows calculation of the user's three-dimensional velocity and the rate of change of his clock. Because of the nature of the satellite system, all calculations are done in earth-centered coordinates and are later converted to local grid systems and datums. The Defense Mapping Agency (DMA) is responsible for specifying and updating the geodetic reference (the WGS-84 geoid will be used), and for providing the parameters to relate GPS coordinates to other grid reference systems.

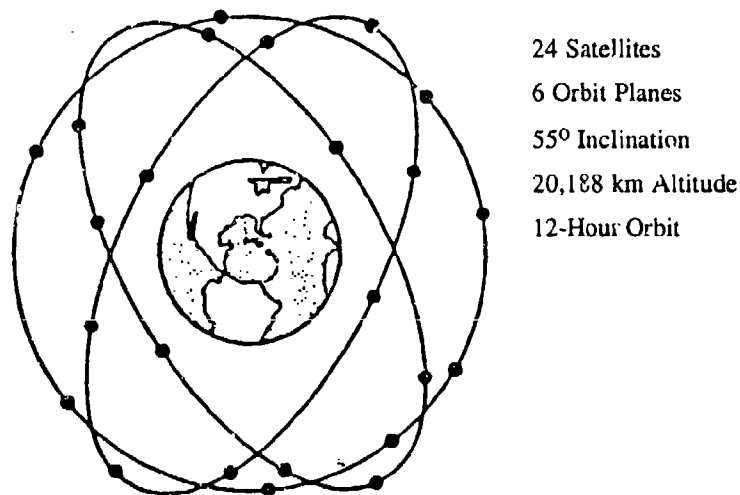


Figure 29. GPS Satellite Orbits (Schematic)

¹ This will be discussed in more detail later.

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B. TECHNICAL PARAMETERS

The GPS signal characteristics are summarized in Figure 30. Satellite signals are transmitted on two L-band frequencies, L₁ at 1,575.42 MHz, and L₂ at 1,227.6 MHz. The use of two frequencies allows more accurate corrections to be made for ionospheric delays in signal propagation time. These signals are modulated with two pseudo-random codes:

- The Clear/Acquisition (C/A) code, which is a short (1,023 bit) Gold code, operating at 1.023 megabits per second (Mbps).
- The precision (P) code, which operates with a 7-day non-repeating cycle² at a rate of 10.23 Mbps, and may be encrypted.

The L₁ signal is modulated with the C/A and P codes in phase quadrature, and the L₂ signal is modulated only with the P code. The purpose of the codes is two-fold: to provide a reference for the timing measurements upon which GPS operation is based and, since the codes are unique to each satellite, to provide a means of identifying individual satellites. In practice, all users, both civilian and military, will have access to the C/A codes, but only selected users who require full system accuracy will have access to the P codes.

Code	Type	Rate	Length
Clear/Acquisition (C/A)	Gold	1.023 Mbps	1023 bits (1 msec)
Precision (P)	PN	10.23 Mbps	2.4 x 10 ¹⁴ bits (257 days) (Reset every 7 days)

Navigation Message: 1500 bits at 50 bits/sec	
-	Contains Clock Corrections, Ephemeris, Ionospheric Model Parameters
-	Handover Word (every 6 seconds)

Link	RF Frequency	Modulation		
		C/A	P	NAV. MSG
L ₁	1565.42 MHz	✓	✓	✓
L ₂	1227.6 MHz		✓	✓

Minimum Received Signal Levels (C/N)		
	C/A	P
L ₁	-163 dBW	-160 dBW
L ₂		-166 dBW

Figure 30. Signal Characteristics

² The P code used by each satellite is actually a 7-day segment of a longer P code, which has a complete cycle of 267 days.

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Both the L_1 and L_2 signals are also modulated with the navigation message, which is 1,500 bits long and is sent at a rate of 50 bits per second (bps). The whole message is 30 seconds long, and is divided into five 6-second subframes. The Navigation Message contains data on the status of the satellite, the time synchronization of the C/A and P codes, and the ephemeris of the satellite. It also contains parameters for computing clock corrections and for computing delays in the propagation of the signals through the atmosphere.

The C/A code is normally acquired first, and transfer to the P code is made by using the handover word (HOW), which is included in each subframe of the Navigation Message. However, users with clocks precisely synchronized to GPS time and with an approximate knowledge of their own position (6 km or better) can acquire the P code directly.

GPS timing accuracy is maintained by Cesium-beam standards at the Master Control Station, and by both Cesium and Rubidium standards on each of the satellites. All frequencies in the satellite (L_1 , L_2 , and the C/A and P-code rates) are derived from the satellite clock which is at a frequency of 10.23 MHz with a maximum uncertainty of less than two parts in 10^{13} per day. The Master Control Station can make adjustments to both the clock frequency and phase, if required.

The last table in Figure 30, which shows the minimum signal levels to be expected at the antenna of a GPS receiver, has been included to show that the signals are indeed extremely weak. For an isotropic (0 dB) antenna, the S/N ratio for the L_1 -C/A signal will be -19 dB. In the absence of any interference or jamming, however, this is more than adequate: the corresponding carrier-to-noise spectral density (C/N_0) will be 39 dB-Hz, and the expected value of E_b/N_0 will be 22 dB.³ Under these conditions, operation should be essentially error-free. However, the system is vulnerable to disruption by relatively low-power jammers. The effects of such jamming will be discussed in Chapter VI of this report.

C. SYSTEM OPERATION

A user with a precise clock synchronized to GPS time could measure the range to a satellite directly by:

- Acquiring the signal and the C/A and P codes.

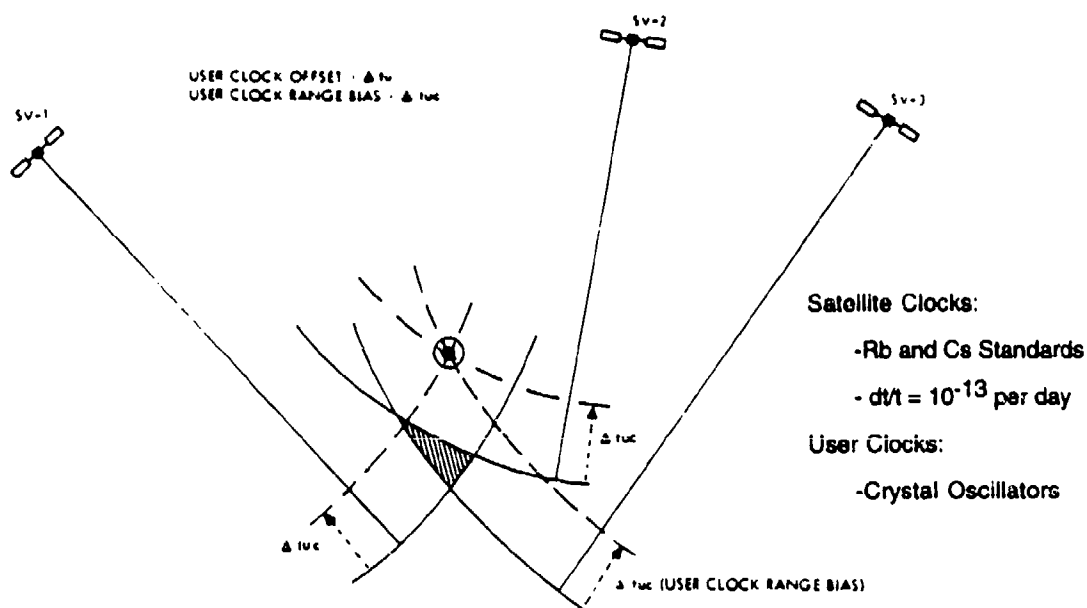
³ The value of C/N_0 and E_b/N_0 assume a receiver noise figure of 5 dB, including all losses.

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- Correlating the received P code with an internally generated replica, and measuring the offset (time delay) between the two codes.
- Using data in the Navigation Message (ephemerides and clock corrections) to determine precisely where the satellite is and when the code was sent.
- Making corrections for ionospheric and tropospheric delays, using data from the satellite, and differential measurements of the L_1 and L_2 signals (to be discussed later).
- Using the corrected time delay and the known speed of propagation of the signal to calculate range.

Similar measurements on two other satellites (a total of three) would allow him to determine his position in three dimensions.

To reduce the cost to the users, GPS receivers are usually equipped with high-quality crystal oscillators rather than Cesium or Rubidium standards. This means that there will be an unknown bias (offset) between the user's clock and the satellite clocks. In this case, the user will measure "pseudo-ranges" to four satellites, all of which will be in error by an amount determined by the clock bias. This is shown (for only three satellites) in Figure 31.



Source: Reference V-2

Figure 31. GPS Pseudorange Measurements

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The result of these measurements is a set of four simultaneous equations:

$$(X_i - U_x)^2 + (Y_i - U_y)^2 + (Z_i - U_z)^2 = (R_i - C_b)^2 \quad i = 1 - 4 \quad (V-1)$$

where:

X_i, Y_i, Z_i = (known) positions of four satellites

U_x, U_y, U_z = (unknown) position of user

R_i = actual range to satellite

C_b = error due to clock bias ($= c\Delta t_u$)

The terms on the right-hand sides of the equations ($R_i - C_b$) are the measured pseudoranges. This gives four equations in four unknowns (U_x, U_y, U_z, C_b), and the user can now solve for his position in three dimensions as well as his clock bias. If more than four satellites are visible, pseudoranges can be measured to all of them, and a maximum likelihood process used to improve the accuracy of the measured position.

D. SYSTEM ERRORS

GPS has been studied in great detail, and the sources of error are well understood and well documented.⁴ The major sources of error are summarized in Table 10. Since the full operational GPS satellite system is not yet in orbit, the actual values of the system errors are not yet known. However, the theoretical analysis has been confirmed by extensive measurements of the existing GPS system as well as by the Timation and Transit satellite navigation systems and is felt to be accurate.

The major expected error sources can be described as follows:

- **Satellite Clock Errors.** The satellite clocks, although highly stable, may deviate from GPS system time by as much as 976 μ s.⁵ The offset is corrected by the GPS receiver, using data from the Navigation Message. Uncorrected errors following this procedure will be 1 nsec or less.

⁴ See, for example, "Global Positioning System," papers published in *Navigation*, Vols. I - III, reprinted by the Institute of Navigation, Washington, D.C. (Ref. V-2). Much of the material in this section is taken from this reference.

⁵ The epoch time of the C/A code is 1 ms. Clock deviation is maintained at less than this value to avoid locking onto the wrong C/A cycle.

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Table 10. GPS Range Error Budget

Uncorrected Error Source	Equivalent Error Source (1σ, meters)
Satellite Clock Errors and Ephemeris Errors	1.5
Atmospheric Delays	2.4—5.2
Group Delay	1.0
Multipath	1.2—2.7
Receiver Noise and Resolution	1.5
User Vehicle Dynamics	1.5
	<hr/> RSS 3.6—6.3 m

- **Atmospheric Delays.** The RF signals from the satellites are both delayed (slowed down) and bent (refracted) in both the troposphere and ionosphere. The tropospheric delay is independent of frequency and is comparatively small. It is predicted and corrected by a relatively simple model which uses measured atmospheric parameters (temperature, pressure, and humidity). The ionospheric correction is more difficult because the ionosphere itself varies seasonally, diurnally, and with solar flare activity. In this case, the delay varies nearly inversely with the square of the frequency and is corrected by measuring the difference in the delay between the L_1 and the L_2 frequencies. If τ_{L1} and τ_{L2} are the delays at L_1 and L_2 , the correction is found from:

$$\Delta\tau = \tau_{L2} - \tau_{L1} = \tau_{L1} \left[\left(\frac{f_{L1}}{f_{L2}} \right)^2 - 1 \right] \quad (V-2)$$

The combined effect of unmodeled tropospheric and ionospheric errors will result in range errors of 2.4 - 5.2 meters.

- **Group Delay.** This is defined as the delay resulting from processing and passing the signal through each satellite. Although this is calibrated during ground tests of the equipment, uncertainties are estimated at 1 meter.
- **Ephemeris Errors.** Satellite orbits are determined by the Master Control Station, based on observations made by the monitoring stations. Errors will be caused by variations in the gravitational potential of the earth, by solar pressure, and by imprecise knowledge of the locations and clock drifts of the

monitoring stations. Errors in the ephemerides will appear as an apparent error in the user's clock, which will be partially compensated by the calculations of user clock bias. The combined effect of uncertainties in the ephemerides and the satellite clocks will result in range errors of about 1.5 meters.

- **Multipath.** Multipath errors are caused by the distortion of the signal that occurs when signals are received over more than one propagation path. It depends on the nature and location of the reflective surfaces peculiar to the user location and will be most severe when the surface is water. Errors are estimated to be from 1.2 to 2.7 meters.
- **Receiver Noise and Resolution.** Receiver noise, and resolution errors resulting from the processing of GPS signals by the receiver hardware and software, will contribute to errors in the range measurements. With high-performance receivers, this error is expected to be less than 1.5 meters.
- **User Vehicle Dynamics.** Motion of the user vehicle will also contribute to errors in range measurements. This can be compensated by proper processing (e.g., Kalman filtering) of the received signals. The estimated error due to receiver noise and resolution, given above, is based on nominal user vehicle dynamics.

The magnitude of the user position errors with GPS is determined by the ranging errors, which have just been discussed, and by a factor determined by the geometry of the four satellites selected for the fix. This factor, called the Geometric Dilution of Precision (GDOP), was originally developed in connection with Loran navigation and has been extended to GPS, which provides locations in three dimensions plus time. An extensive Monte Carlo simulation, based on several thousand users evenly distributed over the globe and in time, has shown that GDOP will increase the errors in user position measurements by a factor of 2.6 (rms).⁶ When combined with the range errors from Table 10, this gives three-dimensional position errors of from 9.4 to 16.4 meters SEP (1σ).⁷

E. SYSTEM PERFORMANCE

It was noted earlier that only selected users would have access to both the C/A and P codes and that most civilian users would use only the C/A code. Those with access to only the C/A code will have their accuracy reduced for two reasons: (1) they will be

⁶ More specifically, 50 percent of the users will have GDOP factors of 2.43 or less, and 90 percent will have GDOP factors of 3.28 or less.

⁷ These are "first-fix" values. If GPS tracking is maintained over a period of time, the noise-like errors will tend to integrate out, and the accuracy will improve.

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making timing measurements with the slower of the two codes (1.023 versus 10.23 Mbps) and, therefore, will have greater timing errors, and (2) they will not be able to use the L₂ signal (which is modulated only with the P code) and, therefore, will not be able to correct for ionospheric delays.⁸

The values in Table 11, which are taken from the Federal Radionavigation Plan, show the expected differences between Precision Positioning Service (C/A and P codes) and Standard Positioning Service (C/A code only). Note that these are 2 σ values, rather than the 1 σ values given earlier and that they are, once again, "first-fix" values.

Table 11. GPS System Accuracy

Service	Accuracy		
	Predictable	Repeatable	Relative
Precision	Horiz - 21 m	Horiz - 21 m	Horiz - 1 m
	Vert - 29 m	Vert - 29 m	Vert - 1.5 m
Standard	Horiz - 100 m	Horiz - 100 m	Horiz - 1 m
	Vert - 140 m	Vert - 140 m	Vert - 1.5 m

F. TIME AND FREQUENCY STANDARDS

Each of the Block II GPS satellites now being launched will have two Rubidium and two Cesium atomic standards, configured to take advantage of the good short-term stability of the Rubidium standard and the excellent long-term stability of the Cesium standard. This will provide long-term stability better than 2 parts in 10¹³ (or an error of about 1 second in 300,000 years).

The frequency standard is used to generate a stable 10.23 MHz clock from which all the GPS frequencies are coherently derived:

P-code chip rate	10.23 MHz
C-code chip rate	1.023 MHz
L1 frequency	1.57542 GHz = 154 x 10.23 MHz
L2 frequency	1.2276 GHz = 120 x 10.23 MHz

⁸ During wartime, it is possible that some portions of the Navigation Message (e.g., ephemeris data and clock corrections) will be encrypted, further reducing the accuracy available to nonauthorized users.

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Any slow drift in the satellite clock frequency is corrected at least once per day by the ground monitor stations, so that all the satellites are synchronized to a common time standard.

In addition, the clock frequency must be corrected for a general relativistic shift due to the difference in gravitational potential between the satellites and the user, and for a special relativistic shift due to their difference in velocity. The correction is given by:

$$\frac{\Delta f}{f} = g_E \frac{R_E}{c^2} \left(1 - \frac{R_E}{R_S} \right) + \frac{1}{2} \left(\frac{v_E^2}{c^2} - \frac{v_S^2}{c^2} \right) \quad (V-3)$$

where:

- R_E = Radius of earth
- R_S = Radius of satellite orbit
- g_E = Acceleration of gravity (9.81 m/s²)
- v_E = Speed of user on earth's surface
- v_S = Speed of satellite
- c = Speed of light (2.998 x 10⁸ m/s)

The correction is made by reducing the frequency of the satellite clock by a factor of 4.45 x 10⁻¹⁰, to a value of 10.22999999545 MHz. The frequency increases as the signal approaches the earth and is seen by the user at its proper value of 10.23 MHz.

G. THE GPS C/A AND P CODES

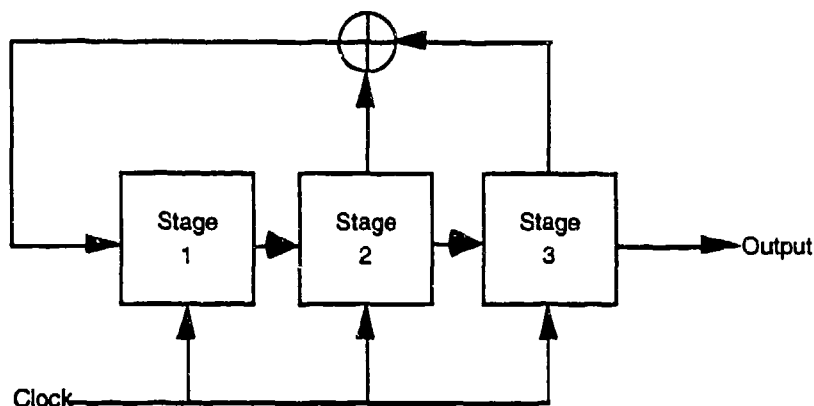
1. Pseudonoise Sequences

A pseudonoise (PN) sequence is a string of binary digits (1s and 0s), formed according to strict mathematical laws, but having statistical properties very similar to those of a random bit stream--or, in the frequency domain, having a spectrum very similar to that of white Gaussian noise.

PN sequences are usually generated by combining the outputs of a *feedback shift register* whose feedback configuration is described by the *generating polynomial*⁹ for the sequence. An example is shown in Figure 32.

$$G(x) = 1 + X^2 + X^3$$

⁹ A subset of these, called primitive polynomials, will generate sequences of maximum length. This is the only type that will be discussed here.



Source: Reference V-5

Figure 32. Three-Stage Linear Feedback Shift Register

In operation, the register is loaded with some initial sequence¹⁰ and is then clocked periodically to shift the contents of each stage one position to the right. In the example shown, the contents of the second and third stages are added modulo 2 during each clock cycle and are fed back to the input to the first stage.

If, for example, the register in Figure 32 were loaded initially with the sequence 001, the output sequence would be 1001011, and this sequence would repeat indefinitely.

Several points concerning PN sequences should be noted because they bear directly on the codes which are used in GPS:

- An n -stage shift register, properly configured, will produce a maximal-length PN sequence of length $2^n - 1$.
- The sequence is completely deterministic. In fact, if $2n$ bits of the sequence are known, it is possible to derive the generating polynomial and to replicate the rest of the PN sequence.
- The output is normally taken from the last stage of the register, as shown in Figure 32. It can equally well be taken from any other stage. The output will be the same sequence, shifted with respect to the original sequence.
- If a PN sequence is added modulo 2 with a shifted sequence of itself, the result is another replica of the same sequence, but with a shift different from either of the first two. This is the *shift-and-add* property.

¹⁰ The all-zero sequence is the only one not permitted. If it were loaded with all zeros, the output sequence will be all zeros.

One of the advantages of PN sequences is their strong autocorrelation function. For the purpose of this paper, the correlation function of two binary sequences, A and B, shifted by k steps with respect to each other, may be defined as:

$$R = \sum_{i=1}^N a(i) b(i+k) \quad (V-4)$$

where N is the length of the sequences, a and b are the elements of the sequences, and the product is taken modulo 2.

If A is a PN sequence and its periodic extension (i.e., the sequence repeated indefinitely) and B is a shifted version of the same sequence, then the equation gives the *autocorrelation function* of the PN sequence. It will have the value N when the relative shift is 0 and the value -1 everywhere else. Since this involves the N -bit PN code and its periodic extension, the correlation peak will repeat every N bits. This is shown in Figure 33.

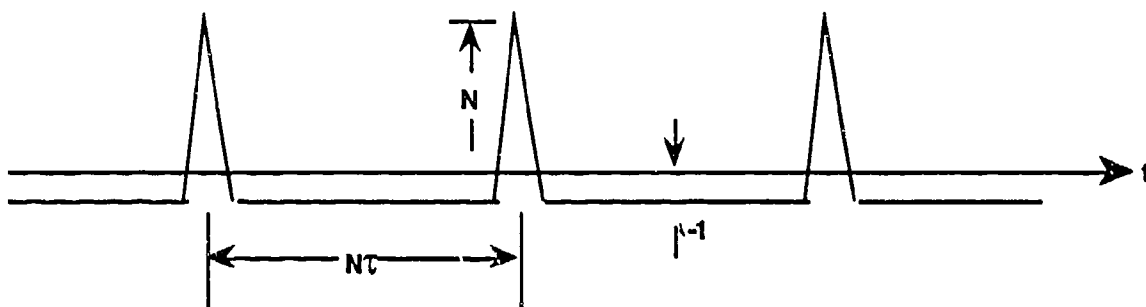


Figure 33. Autocorrelation Function (R) for a PN Sequence of Length N and Bit Width τ

2. The C/A Code

The C/A code, which is also known as the Standard Positioning Service (SPS), is a 1,023-bit Gold code, which is sent at a bit rate of 1.023 Mbps and thus has a period of 1 ms. Each satellite has its own unique C/A code, and transmits it continuously, resetting and repeating the code every millisecond.

The Gold codes are a set of PN sequences of less than maximum length that retain the good autocorrelation properties of other PN sequences, but have minimal cross-correlation peaks with other Gold codes. For the 1,023-bit C/A Gold codes, the autocorrelation peak will have an amplitude of 1,023 units (see Figure 33), and the maximum cross-correlation peak between any two codes will have an amplitude of 65

units. For comparison, the maximum cross-correlation peak for two 1,023-bit maximum-length sequences would have an amplitude of 383 units.

This combination of maximum autocorrelation and minimum cross-correlation is, of course, exactly what is needed for the C/A code. Since all of the GPS satellite signals are on the same frequency (except for offsets due to Doppler shifts), a receiver trying to acquire a specific satellite must rely on code correlation to separate its signal from those of all the other satellites that are visible. The use of Gold codes ensures that the autocorrelation peak will be about 24 dB¹¹ stronger than the maximum cross-correlation peak, so that this task can be accomplished even in the presence of noise or jamming.

Gold codes are usually generated as the modulo 2 sum of certain selected maximal-length sequences.¹² If each of the shift registers used to generate the m-sequences has n stages, the resulting Gold codes will have a period of $N = 2^n - 1$, and there will be a total of $N + 2 = 2^n + 1$ different Gold codes obtainable by shifting the outputs of the two registers with respect to each other prior to the modulo 2 addition. For the C/A codes, $N = 10$, $n = 1023$, and the two generating polynomials are:

$$G_1 = 1 + X^3 + X^{10}$$

$$G_2 = 1 + X^2 + X^3 + X^6 + X^8 + X^9 + X^{10}$$

The resulting Gold code will be:

$$G(t) = G_1(t) \oplus G_2(t + N_i \tau_c) \quad (V-5)$$

where: N_i = Number of bits of offset between G_1 and G_2
 τ_c = Chip width of C/A code (0.9775 μ s)

Several points should be noted:

- Both shift registers are set to the "all ones" state at the beginning of each period of the C/A code. This is done in strict synchronism with corresponding epochs of the P code and the message data bits.
- The shifted versions of the G_2 code are derived by tapping into the G_2 shift register at two points and modulo 2 adding the sequences at these points to get G_{2i} . This uses the shift-and-add property, which was mentioned earlier.

¹¹ Doppler shifts in the satellite signals affect the process by making the codes drift with respect to each other. However, even under worst-case conditions, the ratio is still 21.6 dB.

¹² They are selected from the set of *preferred* sequences. For a discussion of these, and for more detail on the Gold and other codes, see Reference V-3.

A schematic diagram of the C/A code generator is shown in Figure 34.

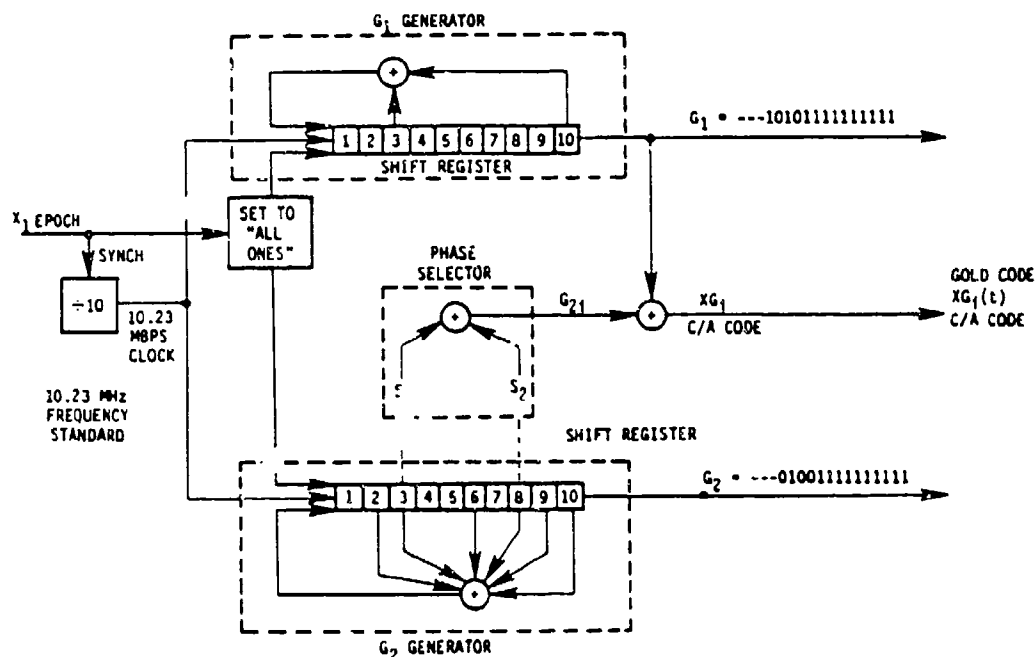


Figure 34. C/A Code Generation

- Since there are 1,023 shifts of G_2 relative to G_1 , 1,023 different Gold codes can be produced by this technique. The G_1 and G_2 codes themselves are the other two numbers of the total family of 1,025 Gold codes that can be generated by these registers.
- The settings of the two feedback taps on G_2 will be different for each satellite, thus giving each one its own unique C/A code.

3. The P Code¹³

The Precision (P) code, also known as the Precision Positioning Service, is a long PN sequence that is sent at 10.23 Mbps and is used for accurate position location. It is generated as the modulo 2 sum of two maximal-length sequences, X_1 and X_2 . Each is generated by a 24-stage shift register and would have a length of $2^{24}-1 = 16,777,215$ bits if

¹³ Since January 1994, all P Code transmissions have been encrypted, to reduce the chance of an enemy's spoofing the GPS system. The encrypted version of the P Code which is called the Y Code, can be used only by selected users who are equipped with the proper decoders and crypto keys.

the sequences were allowed to run to completion. Instead, the X_1 code is truncated at 15,345,000 bits. This gives it a period of 1.5 seconds, which is commensurate with all the other GPS waveforms: the period of the C/A code (1 ms), the length of a data bit (20 ms), and the length of a subframe of the navigation message (6 seconds). All the waveforms can therefore be maintained in strict synchronism. The X_2 code is made 37 bits longer. We thus have:

X_1 : a PN code of length 15,345,000

X_2 : a PN code of length 15,345,037

The P code is formed as the modulo 2 sum of these, using a circuit similar to that shown in Figure 34.

$$P(t) = X_1(t) \oplus X_2(t + N_i \tau_p) \quad (V-6)$$

where: N_i = Number of bits of offset between X_1 and X_2 ($0 \leq N_i \leq 36$)

τ_p = Chip width of P code (97.75 nsec)

Since X_1 and X_2 are relatively prime (i.e., have no common denominator), the period of the P code is the product of the periods of the X_1 and X_2 codes, or 2.35×10^{14} bits. If allowed to run without being reset, it would have a period of just over 38 weeks. Instead, both the X_1 and X_2 codes (and thus the P codes) are reset and restarted at the beginning of each week.

Changing the value of the offset ($N_i \tau_p$) causes the P code to start in a different place, and there are 37 different starting places. Each satellite is assigned a different value of N_i which gives it a unique, non-overlapping P code. Each satellite is, in effect, given a 1-week segment of the P code, and the entire system is reset and restarted at the beginning of each week.

4. The Navigation Message

Each satellite transmits a navigation message which contains the following information:

- Clock corrections showing the offset (if any) between the satellite clock and GPS standard time
- Satellite ephemerides: a set of orbital parameters which permit the satellite orbit to be calculated precisely.

- Ionospheric delay model and parameters for use by users who do not have access to both the L_1 and L_2 frequencies.
- Satellite health and the elapsed time since the last update of ephemerides and clock corrections.
- Each almanac containing the orbital parameters of all the satellites in the GPS constellation. It is less accurate than the data that the satellite provides on its own orbit and would be used to acquire new satellite signals or to select an optimum group of satellites for navigation in a given region.

The basic navigation message is 1,500 bits long, is transmitted at 50 bps, and repeats every 30 seconds. This message frame is divided into five subframes, as shown in Figure 35.

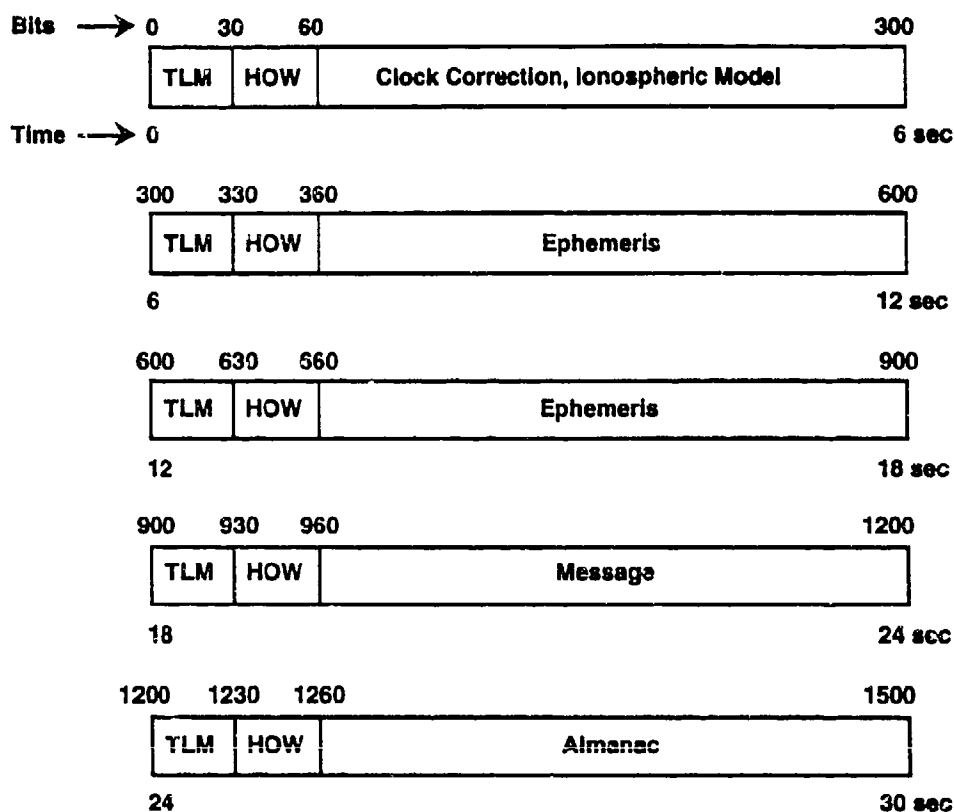


Figure 35. Navigation Message

- The **telemetry (TLM) words** are used by the satellite to communicate with the ground control segment. Such things as satellite health, diagnostic data, and acknowledgment of receipt of clock and ephemeris corrections would be sent.

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- The **handover word** (HOW) is used in the acquisition process. A running count (called the Z-count) is kept of the number of 1.5-second periods of the X_1 code which have elapsed since the system was reset at the beginning of the week. The HOW contains the Z-count at the leading edge of the next subframe. Thus a user who has acquired only the C/A code can read the HOW and acquire the P code at the beginning of the next subframe.
- The **message block** is generated by the ground control segment and is used to pass data to GPS system users.
- The **almanac block** contains data on one other satellite in the GPS constellation, and this block will change with every repetition of the navigation message. It requires 25 frames,¹⁴ or 12.5 minutes, for the complete almanac to be sent.

5. Signal Synchronization

It is worthwhile to summarize the steps that have been taken to ensure the exquisite synchronization of the GPS signals since it is this synchronization, combined with the precise frequency standard, that gives GPS its accuracy: The C/A code is 1,023 bits long, because it is derived as the product of two maximal-length PN sequences. The master clock frequency is therefore chosen to be 10.23 MHz, both to ensure that there are an integral number of RF carrier cycles in each bit of the C/A code, and so that the C/A code (which is clocked at 1.023 MHz) is exactly 1 ms long. The P code is clocked at 10.23 MHz so that, once again, there are an integral number of RF carrier cycles in each code bit,¹⁵ and the X_1 component of the P code is truncated at 1.5 seconds so that its period is exactly one-quarter of the length of a subframe of the navigation message. Finally, all of these signals are derived from the same master clock so that they remain synchronous, in-phase, and coherent.

H. ORBITAL CONSIDERATIONS

As noted earlier, the GPS satellites are in circular prograde orbits, inclined at 55° to the equator, and with a 12-hour sidereal period. There will be four satellites in each orbit, spaced at 90° intervals, and the positions will be staggered so that a satellite will see satellites in adjacent orbits at 45° ahead of and behind it.

The radius of the satellite orbit is given by:

¹⁴ There will be 24 satellites in orbit. The 25th frame is blank and is reserved for future use.

¹⁵ True for both the L_1 and L_2 frequencies, since both are multiples of the master clock frequency.

$$R_S^{3/2} = \frac{P\sqrt{\mu}}{2\pi} \quad (V-7)$$

where: P = Orbital period (43,082 sec)
 μ = Gravitational parameter ($3.98771 \text{ m}^3/\text{s}^2$)

from which

$$R_S = 26,566 \text{ km}$$

and the altitude of the satellite orbit is

$$\begin{aligned} H_S &= R_S - R_E \\ &= 20,188 \text{ km} \end{aligned}$$

where: R_E = Earth radius = 6,378.15 km

The relative geometry of an orbiting satellite and a user at or near the surface of the earth leads to several complications for the GPS system. Consider, for example, the range from the user to a satellite, for the case in which the satellite passes directly overhead (see Figure 36):

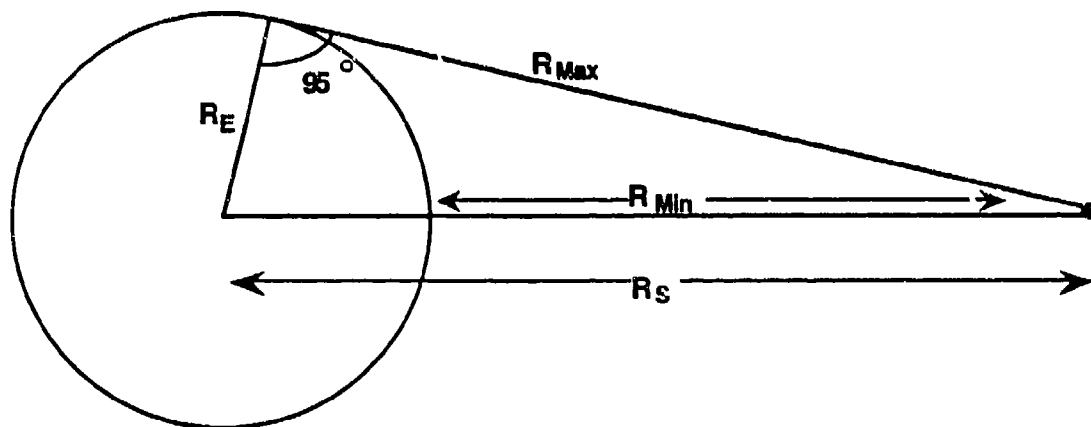


Figure 36. Distance From User to Satellites

The minimum range, when the satellite is directly overhead, is 20,188 km. The maximum range, when the satellite is at its lowest useful elevation angle of 5° above the horizon, is found to be 25,239 km. Thus, approximately every 3 hours, there is a change in the user-satellite range of:

$$\Delta R = R_{Max} - R_{Min} = 5,051 \text{ km} \quad V-8$$

or, in terms of the parameters of the GPS system:

$$\begin{aligned}
 \Delta R &= 16.848 \text{ ms} \\
 &= 26.5 \times 10^6 \text{ cycles of the L1 frequency} \\
 &= 20.7 \times 10^6 \text{ cycles of the L2 frequency} \\
 &= 1.72 \times 10^5 \text{ chips of the P-code} \\
 &= 1.72 \times 10^4 \text{ chips of the C/A - code} \\
 &= 16.85 \text{ complete C/A code periods (1,023 bits)}
 \end{aligned}$$

An even more significant problem is the Doppler shift caused by the relative motion of the satellite and the user. Consider first a stationary observer at the North Pole, where there is no motion of the observer due to the rotation of the earth (see Figure 37):

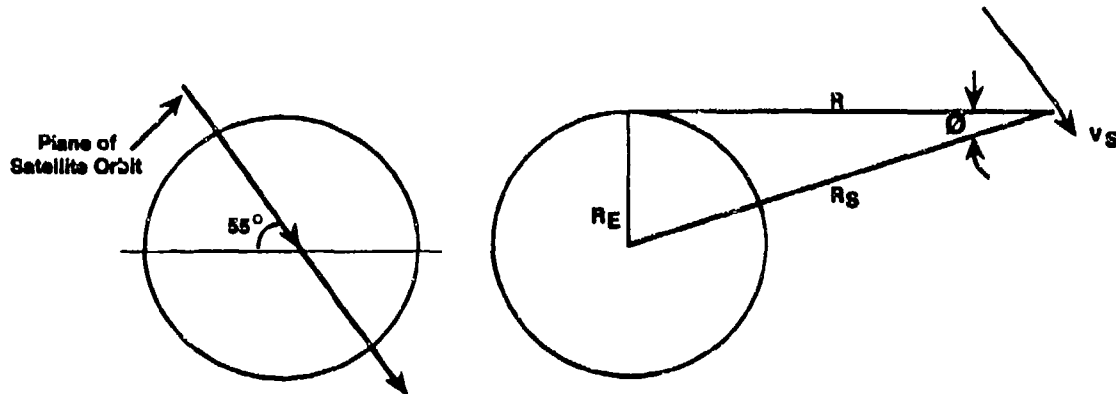


Figure 37. Doppler Geometry for User at North Pole

Calculating the values of the quantities in Figure 37 gives:

$$\begin{aligned}
 R &= 25,789 \text{ km} \\
 v_S &= 3.874 \text{ km/sec} \\
 \theta &= 13.892^\circ
 \end{aligned}$$

There will be no Doppler shift as the satellite passes directly over the user at its closest point of approach and a maximum Doppler shift as the satellite reaches the horizon. At this point, the radial velocity of the satellite as seen by the user is given by.¹⁶

¹⁶ (U) The author extends his thanks to Dr. Hamilton Hagar of IDA for deriving this formula.

$$\dot{R} = \frac{R_E}{R} \sqrt{\frac{\mu}{R_S}} \sqrt{\sin^2(55^\circ) - \sin^2(13.892^\circ)} \quad V-9$$

$$= 0.7504 \text{ km/s}$$

At the L1 frequency (1.57542 GHz), this gives a Doppler shift of 3,944 Hz. This will be seen as a positive shift (an apparent increase in the L1 frequency) as the satellite rises over the horizon, will drop to zero as the satellite passes overhead, and will become an equal but negative shift as the satellite falls below the opposite horizon 6 hours later. A user who is observing two satellites near the horizon in opposite directions will see a total Doppler shift between them of nearly 8,000 Hz.

For a user at the horizon, the situation is complicated by the fact that the rotation of the earth produces a tangential velocity of $v_E = 0.4651 \text{ km/s}$. This must be added vectorially to the satellite velocity to find the relative velocity of the satellite with respect to the user. When this is done and the appropriate geometric corrections are made, the Doppler shift is found to be 4576 Hz. As before, this will be a positive shift as the satellite rises over the horizon and a negative shift as it sets over the opposite horizon. The total shift between low-angle satellites seen in opposite directions will be more than 9,000 Hz.

Finally, there will be a Doppler shift due to the user's own velocity. The magnitude and sign of the shift will depend on the angle between the velocity vectors of the user and the satellite but, for a user moving at Mach 1, the maximum values are:

Altitude	Speed of Sound	Doppler Shift
0	761.6 mph	1,789 Hz
10K ft	734.9 mph	1,726 Hz
30K ft	678.5 mph	1,594 Hz

For a user who is already locked onto and tracking one or more satellites, these periodic changes in satellite range and Doppler shift due to satellite motion can be accommodated because the motion of the satellites is well known, and the tracking loops in the receiver can be programmed to follow the changes very precisely. Changes in the Doppler shift due to the user's own motion is harder to follow, especially during accelerations or turns, and may require increasing the bandwidth of the tracking loops to

avoid losing lock. This, in turn, will reduce the accuracy of the GPS receiver and will also make it more susceptible to jamming.

The problem is more acute for a user who is trying to acquire and lock onto satellite signals for the first time. To do this, he must search over a time and frequency space whose size is determined by:

- His lack of knowledge of his own position and velocity
- His lack of knowledge of GPS time
- His lack of knowledge of satellite ranges and Doppler shifts.

The complexity of the search and the time to first fix increase as any of these uncertainties increases.

I. GLONASS

The Soviet Union developed a satellite system called GLONASS that, like GPS, was intended to provide accurate worldwide navigation. Since the two systems have the same function, it is not surprising to find many similarities. On the other hand there are also some very significant differences, particularly in the technical parameters of the navigation signals.¹⁷

Satellite System. Both GPS and GLONASS have 24 satellites. The orbital parameters, however, are quite different, as shown in Table 12.

Table 12. GPS and GLONASS Satellite Orbits

Parameter	GPS	GLONASS
Number of satellites	24	21 + 3 spares
Orbital planes	6, spaced by 60°	3, spaced by 120°
Orbital plane inclination	55°	64.8°
Orbital radius ^a	26,560 km	25,510 km
Orbital height ^a	20,180 km	19,100 km
Orbital period	1/2 sidereal day (11 hr. 58 min)	8/17 sidereal day (11 hr. 16 min)

^a There are minor inconsistencies between these values and the values given in the earlier section on Orbital Considerations.

¹⁷ Much of the material for this section is taken from *GPS World* magazine, particularly the November/December 1990 issue.

Navigation Signals. The similarities and differences between the signal parameters of GPS and GLONASS are covered in the following discussion and in Table 13.¹⁸

- Similarities:**
- Both systems operate at frequencies of approximately 1.2 and 1.6 GHz.
 - Both transmit on two separate frequencies so that the users can make corrections for ionospheric time delay.
 - Both use a short, moderate-speed (C/A) code for acquisition and a longer, high-speed (P) code for precise navigation. In both systems, the P Code is available only to selected users.
 - Both transmit a navigation message, which contains time corrections and satellite ephemerides.
- Differences:**
- GPS uses code division multiple access (CDMA): all the satellites transmit on the same frequency and are identified by their different C/A and P codes. GLONASS uses frequency division multiple access (FDMA): each satellite transmits on a different pair of frequencies, and all have the same C/A and P codes.
 - GPS uses a Gold code for its C/A code, while GLONASS uses a maximal-length PN sequence. Both use m sequences for the P codes.
 - The code clock frequencies used in GPS are roughly twice those used in GLONASS.

Table 13. GPS and GLONASS Navigation Signals

Parameter	GPS	GLONASS
Signal division method	CDMA	FDMA
Carrier frequencies	L ₁ = 1,575.42 MHz L ₂ = 1,227.60 MHz	L ₁ = (1,602 + k x 9/16) MHz L ₂ = (1,246 + k x 7/16) MHz where: k = channel number = 0, 1, 2, ... 24
Code clock rates	C/A = 1.023 MHz P = 10.23 MHz	C/A = 0.511 MHz P = 5.11 MHz
C/A Code Length	1023 bits	511 bits
Crosstalk between adjacent channels	-21.3 dB	-48 dB

¹⁸ The terms L₁, L₂, C/A, and P are not used by the GLONASS system. They are used here for both systems to facilitate the comparison.

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Navigation Message. Both GPS and GLONASS transmit a low data rate (50 bps) navigation message, which includes such information as clock corrections, satellite health, and satellite orbital parameters. The similarities and differences are shown in Table 14:

Table 14. GPS and GLONASS Navigation Messages

Parameter	GPS	GLONASS
Data rate	50 bps	50 bps
Total message length	12.5 min	2.5 min
Subframe length	30 sec	30 sec
Reference geoid	WGS 84	SGS 85
Reference time	UTC (Greenwich)	UTC (Moscow)
Clock data	Clock & frequency offset, frequency rate	Clock & frequency offset
Orbital data	Modified Keplerian orbital elements	Satellite position, velocity, and acceleration (plus solar & lunar corrections)

Joint Use of GPS and GLONASS. Each of these systems, when fully deployed, will provide accurate worldwide navigation. Each will have from 6 to 11 satellites visible at any given time to users anywhere on or above the surface of the earth, and the predicted accuracies (1 drms) are shown in Table 15:

Table 15. Accuracy of GPS and GLONASS

Parameter	GPS	GLONASS
Position - Horizontal	10 m	100 m
- Vertical	15 m	150 m
Speed	3 m/sec	15 m/sec
Time	10 nsec	1 msec

Several comments should be made about these values:

- The fact that the GLONASS code clock rates are one-half of the GPS rates should mean that GLONASS accuracy would be one-half that of GPS. The greater discrepancy shown in Table 15 is unexplained, but could be due to lower clock stability, to poorer signal synchronization, or just to more conservative estimates on the part of the Soviet designers.
- The accuracy of a satellite navigation system depends not only on the precision of the navigation signals but also on the geometry of the satellites at the time

the measurements are taken. The values given above are averages and may vary by as much as a factor of two.

- The above values are for the satellite system (GPS or GLONASS) alone. The accuracy can be significantly improved, especially for a moving platform, by using both GPS and/or GLONASS and an inertial system (INS) and combining the two in a Kalman filter. A recent analysis¹⁹ has shown that such a system, using GPS, will give a consistent accuracy of 7 meters circular error probable (CEP).

It should also be noted that GPS includes a feature called Selective Availability (SA) which, when activated, deliberately reduces the precision of GPS to no less than 100 meters (2 drms) 95 percent of the time. This is accomplished by making pseudorandom changes in the satellite clocks and in the ephemeris data in the navigation messages. Authorized users will be given the crypto keys required to correct these changes, but others will have to use the system with reduced accuracy. Both the Soviet and Russian governments have stated that GLONASS has no such feature.

It is tempting to consider joint use of GPS and GLONASS, and experimental systems are being built to accomplish this. A user will see from 12 to 22 satellites at any given time, thus ensuring better reliability and better satellite geometry; the user would be protected against degradation or failure of either system; and navigation accuracy would be improved by the greater volume of data available to the user. However, the two systems are sufficiently different that combining them will not be easy:

- The signal formats and navigation messages are completely different so that a separate receiver and processor will be required for GPS and GLONASS.
- Since the coordinate systems, time references, and orbital parameters are different, it will not be possible to directly compare pseudorange measurements from GPS and GLONASS. Instead, separate navigation solutions must be found, converted to a common coordinate system, and then combined.

At best, the combined GPS/GLONASS receiver could share a common RF preamplifier, master oscillator, power supply, and display. Except for these, two separate receivers will be required, and additional computer capacity will be needed to combine their outputs.

¹⁹ See Reference V-1.

REFERENCES

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VI. COMPARISON OF RADIONAVIGATION SYSTEMS

Each of the major global radionavigation systems (Loran, Omega, Transit, and GPS) represented the technological state of the art at the time it was introduced, and each still has one or more features that are not easily duplicated by any of the other systems: GPS is the most accurate, Transit is the simplest and least expensive, Loran is probably the least vulnerable to deliberate jamming, and Omega provides worldwide coverage without reliance on satellites and also penetrates sea water enough so that it can be used by a submarine at an (antenna) depth of 15 meters. Each of these systems has tens or hundreds of thousands of users, many of whom rely exclusively on one system. The questions of which is best and which should be phased out are not easily answered.

A. COMPARISON OF RADIONAVIGATION SYSTEMS

Table 16 lists most of the common radionavigation aids and shows their RF carrier frequencies, the number of ground stations or satellites, and the number of users of each system (as of 1993).¹

The worldwide systems discussed in this paper either operate at very low frequencies (Loran and Omega) to achieve long propagation ranges or rely on satellites (Transit and GPS) for wide-area coverage. The other systems shown in the table are all line-of-sight limited² and, therefore, are effective only over a relatively small area.

Table 16 also shows that, in almost all cases, the number of civilian users is far greater than the number of military users. This is true even for those systems (Loran, Transit, and GPS) that were originally developed by the military for their own use, and it leads to some severe constraints in both the operation of and planning for the systems. For

¹ JTIDS and PLRS are military systems that perform both navigation and communication functions. Although their accuracy is adequate for almost all applications, they have some significant operational limitations: They are transponder-based systems, which require each user to have an active transmitter and to be within radio range of three or more other system users; and they are "communal" systems in which each user finds his position first with respect to other users and then, either directly or indirectly, with respect to two or more control stations at known locations.

² Except for radiobeacons, which operate in the same frequency band as commercial AM radio, and have ground wave ranges which extend beyond the horizon and skywave ranges which may reach several thousand miles.

example, a good case could be made that Loran should be phased out and replaced by GPS. However, there are more than half a million Loran users, many of whom rely on it as their only form of radio navigation and, since aircraft or marine GPS receivers cost \$2,000 or more, many of them are reluctant to change.

Table 16. Radionavigation Aids

System	Frequency (MHz)	Number of Stations	Number of Users	
			DoD ^a	Civilian
Omega	0.010-0.013	8	3,825	23,600
Loran-C	0.100	46 ^b	450	686,600
Radiobeacons	0.200-1.6	1,903	11,285	677,000
ILS	108-112; 329-335	1,154	9,500	127,000
VOR	108-118	1,105	12,000	197,000
PLRS	420-450	1 Master/Net	2,000	
Transit	150; 400	7 satellites	100	85,000
JTIDS	960-1,215		<100	
DME	960-1,213	1,105	12,000	89,500
Tacan	960-1,215	813	13,000	<100
GPS	1,227; 1,575	24 satellites	17,000	23,700
MLS	5,031-5,091	99	1,300	100

^a Includes other U.S. Federal and non-U.S. military

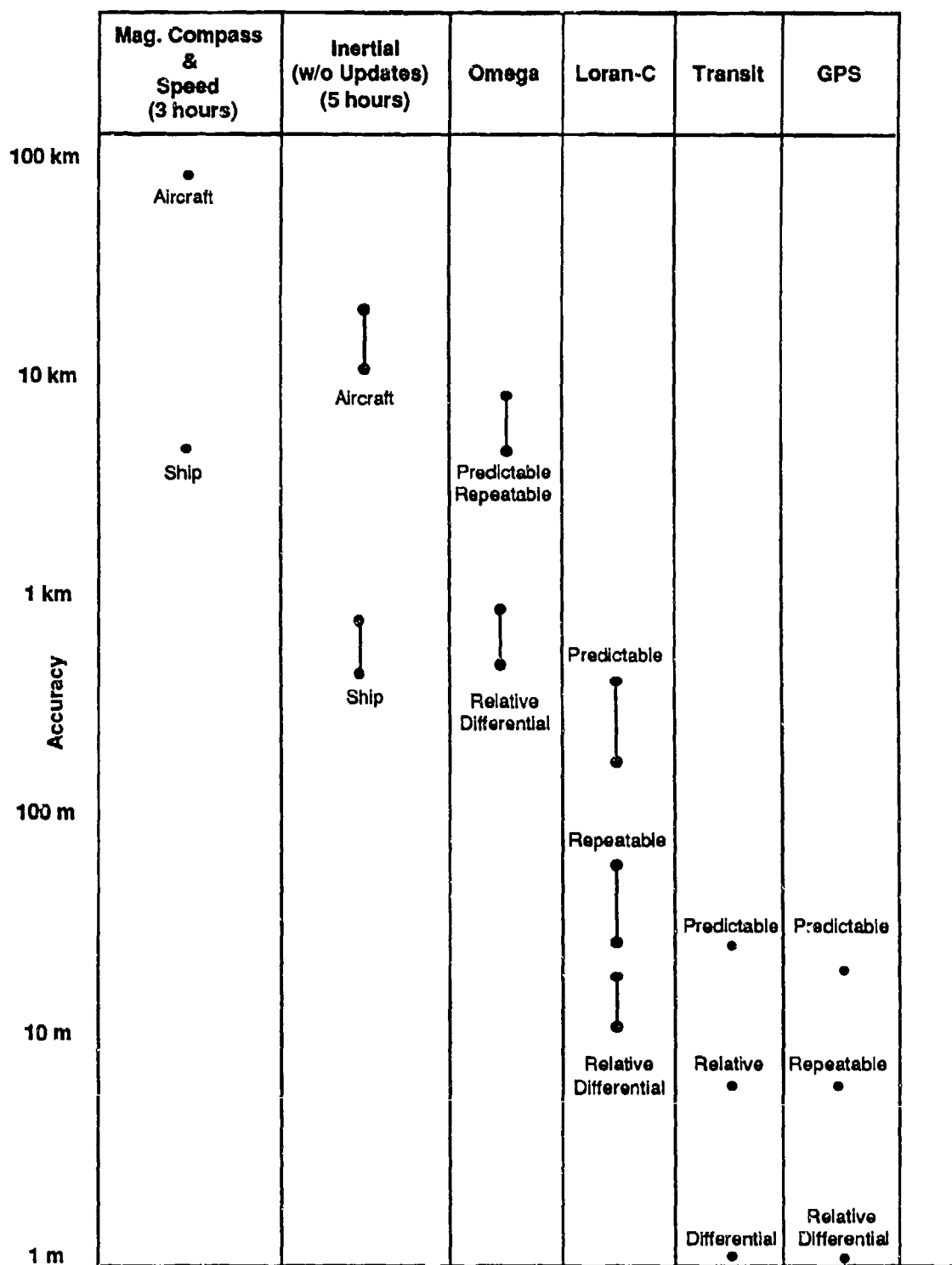
^b U.S. only

The accuracies of the four worldwide navigation systems are compared in Figure 38. Note that for the two ground-based systems (Loran and Omega) there is a range of accuracies, depending on the user's distance from the transmitters and his position in the grid. For the two satellite-based systems, there are no such restrictions, and only single values are given.

Two other navigation systems are included for comparison:

- A system using only a magnetic compass and a speed indicator, where it is assumed that the compass is accurate (and can be followed) to about 2° and that the speed can be measured to an accuracy of about 3 percent. After three hours, a 500-knot airplane will have a navigation error of 90 km, and a 20-knot ship will have an error of about 3.5 km.
- An inertial-only system using a typical commercial INS with a drift rate of 0.1 to 0.25 degrees per hour. After 5 hours, the 500-knot aircraft will have a navigation error of 10-20 km, and the 20-knot ship will have an error of 400-800 meters.

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Note: Adapted from Reference VI-5.

Figure 38. Navigation System Accuracy

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This comparison is probably not fair because these are dead-reckoning systems whose errors accumulate over time, while the worldwide radionavigation systems provide independent location readings each time they are used. However, this is precisely the reason that the worldwide systems were developed: Dead-reckoning systems whose errors increase continually and unpredictably are not suitable for long-range navigation.

Table 17 presents a final comparison of the four worldwide navigation systems which have been discussed in this paper. A few comments should be made to clarify the comparison:

- Loran-C does not provide worldwide coverage since its reliable range is limited to about 1,200 nmi for the ground wave and 2,000 nmi for the skywave (with reduced accuracy). However, the existing Loran stations provide continuous coverage of major portions of North America, Europe, the Mideast, as well as the air and ship lanes across both the North Atlantic and North Pacific.
- GPS is the only system that provides a direct readout of both position and velocity. Transit cannot do so because the Doppler shift is the variable that is measured to determine position. Although it would be theoretically possible to determine velocity from the measured Doppler shifts of Loran and Omega signals, the shifts are so small (3.4×10^{-4} Hz/kt per knot for Loran and 3.5×10^{-5} Hz/kt per knot for Omega) that the measurements are not practically possible.
- GPS uses CDMA and GLONASS uses FDMA (see Chapter V) to permit signals from several satellites to be processed simultaneously. On the other hand, all the Transit satellites use the same frequencies and message formats, so the signals from two or more satellites could not be separated and would interfere with each other. Transit, therefore, is limited to one satellite in view, and a minimum time between fixes of 30 minutes or more. This was no problem for the Polaris submarines, which did not need continuous fixes (and, in fact, did not want them, since they had to surface to receive the Transit signals), but it does make Transit the only system that cannot provide continuous coverage.
- Both Loran and Omega penetrate seawater to some extent and can be received by submerged submarines: Loran to an antenna depth of 2-3 meters, and Omega to an antenna depth of 15 meters.

GPS is clearly the best of the four systems when judged by accuracy and performance (three-dimensional measurements of both position and velocity), and Transit is the least desirable, primarily because of its lack of continuous coverage and the problems

Table 17. Comparison of Worldwide Radionavigation Systems

System	Accuracy			Coverage		Measured Value		Fix Dimension	Ambiguity	Phaseout Date
	Predictable	Repeatable	Relative	Worldwide	Continuous	Position	Velocity			
Loran-C	460-920 m	20-100 m	10-20 m	No	Yes	Yes	No ^a	2D	No	
Omega	2-4 nmi (3.7-7.4 km)	2-4 nmi (3.7-7.4 km)	0.25-0.5 nmi (460-930 m)	Yes	Yes	Yes	No ^a	2D	Yes	2005
Transit	25 m	15 m	7 m	Yes	No ^b	Yes	No	2D	No	1996
GPS	Horiz 21 m Vert 29 m	Horiz 21 m Vert 29 m	Horiz 1 m Vert 1.5 m	Yes	Yes	Yes	Yes	3D	No	

^a Theoretically possible but not practical. See text.

^b Limited by satellite availability. See text.

involved in using it on moving platforms.³ A case can be made for continued operation of both Loran and Omega, and this will be presented in the last section of this chapter.

B. JAMMING AND INTERFERENCE

One of the important measures of performance for any navigation system is its ability to operate in the presence of interference: either natural or man-made noise, or deliberate jamming. This section will analyze the performance of GPS, Loran, and Omega and will draw some (perhaps surprising) conclusions concerning their availability when faced by enemy countermeasures. Transit will not be considered, since it is due to be phased out soon, but its vulnerability should be similar to that of GPS.

1. GPS Jamming

The pertinent parameters of the GPS system are summarized below:

- The GPS signals are extremely weak: The C/A signal on the L_1 carrier has a level of -163 dBW. This is, in fact, significantly below the level of thermal noise, and the S/N ratio at the antenna is -19 dB.
- The process of demodulating the C/A code down to the 50 Hz bandwidth of the navigation message provides a processing gain of 43 dB and gives a signal level (E_b/N_0) inside the receiver of 22 dB.⁴
- More sophisticated GPS receivers can lock onto and track the RF carrier. This increases timing accuracy since they are now referenced to a carrier cycle (0.67 ns at 1.5 GHz) rather than to a chip of the C/A code (1 μ s) or the P code (0.1 μ s). For these receivers, the tracking filter bandwidth can be reduced from 50 Hz to 1 Hz or less, thus providing an additional 17 dB of processing gain, and giving a carrier-to-noise spectral density ratio (C/N_0) of 39 dB-Hz. This provides an extremely precise measurement technique, but it is very sensitive to disturbances: any sudden unexpected acceleration of the vehicle or any RF noise (interference or jamming) can cause the tracking filters to lose lock. Inertial aiding of the GPS system can help to mitigate this.
- Since GPS is a satellite-based system, the received signal levels are essentially the same anywhere on the surface of the earth. This is in contrast to Loran and

³ Transit service will be discontinued in 1996.

⁴ This assumes a receiver noise figure, including all losses, of 5 dB. The P code has a code rate and an RF bandwidth 10 times that of the C/A code. It thus sees 10 dB more thermal noise, but has 10 dB more processing gain. The value of E_b/N_0 will be the same for both.

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Omega, where the signal strengths increase and jamming becomes more difficult as the receiver approaches the transmitter.

The performance of GPS systems in the face of interference has been extensively studied, both theoretically and experimentally, and is well understood.⁵ The values of C/N for which the carrier loop and code loop will lose lock are shown in Table 18 for both a stand-alone (unaided) GPS receiver and for one that is aided by an integrated inertial system. In the latter case, the INS helps the GPS to maintain tracking through sudden short bursts of noise or interference and improves the loss-of-lock level by 3-6 dB.

Table 18. C/N Values for Loss of Lock (dB-Hz)

Loop	Unaided	Aided
Carrier	27	24-21
Code	15	9-12

The relation between C/N and the noise jammer power level is given by:⁶

$$C/N = \frac{C}{N_o + J/2B} \quad (VI-1)$$

$$= \frac{C/N_o}{1 + (J/S)(C/N_o)(1/2B)} \quad (VI-2)$$

where:

- C = S = Signal power level
- N_o = Noise power spectral density
- J = Jammer power level
- B = Processing bandwidth
- = 1/R_c where R_c is the PN code chip rate

When the jamming is small [(J/S) (C/N_o) (1/2B) << 1], we have C/N = C/N_o, and when the jamming is large [(J/S) (C/N_o) (1/2B) >> 1] the equation becomes (with all quantities in dB):⁷

⁵ The values used here are taken from an unpublished study by System Control Technology, Inc. The study was funded by DARPA and was performed under an IDA contract. It will be the subject of a subsequent IDA report.

⁶ The second equation is often more useful because it specifically shows the jammer-to-signal ratio, J/S.

⁷ This is valid for a noise jammer. For a CW jammer, the constant is R_c rather than 2R_c.

$$C/N + J/S = \text{Constant} = 2R_c \quad (\text{for } J/S \text{ large}) \quad (\text{VI-3})$$

For the P code, the chip rate is 10.23 MHz, and the constant $2R_c$ is 73 dB. Curves showing the degradation of C/N with increasing levels of jamming (J/S) are shown in Figure 39 for initial C/N_0 values of 20, 30, and 40 dB-Hz.

For nominal (unjammed) operation of GPS, the value of C/N_0 is almost 40 dB. From the curves of Figure 39, it is seen that the values of C/N which cause loss of carrier loop lock (27 dB) and code loop lock (15 dB) in the unaided case correspond to J/S ratios of about 46 dB and 58 dB respectively.

The J/S ratio as a function of jammer transmitter power and jammer-receiver distance is calculated using the following parameters:

- The GPS receiver is operating at the L_1 frequency (1,575.42 MHz)
- The receiver is operating with the P code ($R_c = 10.23$ MHz) at a received signal level of -163 dBW.
- The jammer antenna is a quarter-wave vertical stub on a ground plane, with a gain of 3 dB
- The jammer has clear line of sight to the GPS receiver, and the free-space loss equation applies:⁸

$$\text{Loss} = 32.44 + 20 \log d + 20 \log f \text{ db} \quad (\text{VI-4})$$

where: $d = \text{Distance (km)}$
 $f = \text{Frequency (MHz)}$

Curves of these functions are shown in Figure 40. The values of J/S for the loss of both carrier and code loop lock are shown.

⁸ This will be difficult to realize in practice. Longer ranges will require that the jammer, the victim GPS receiver, or both, be airborne.

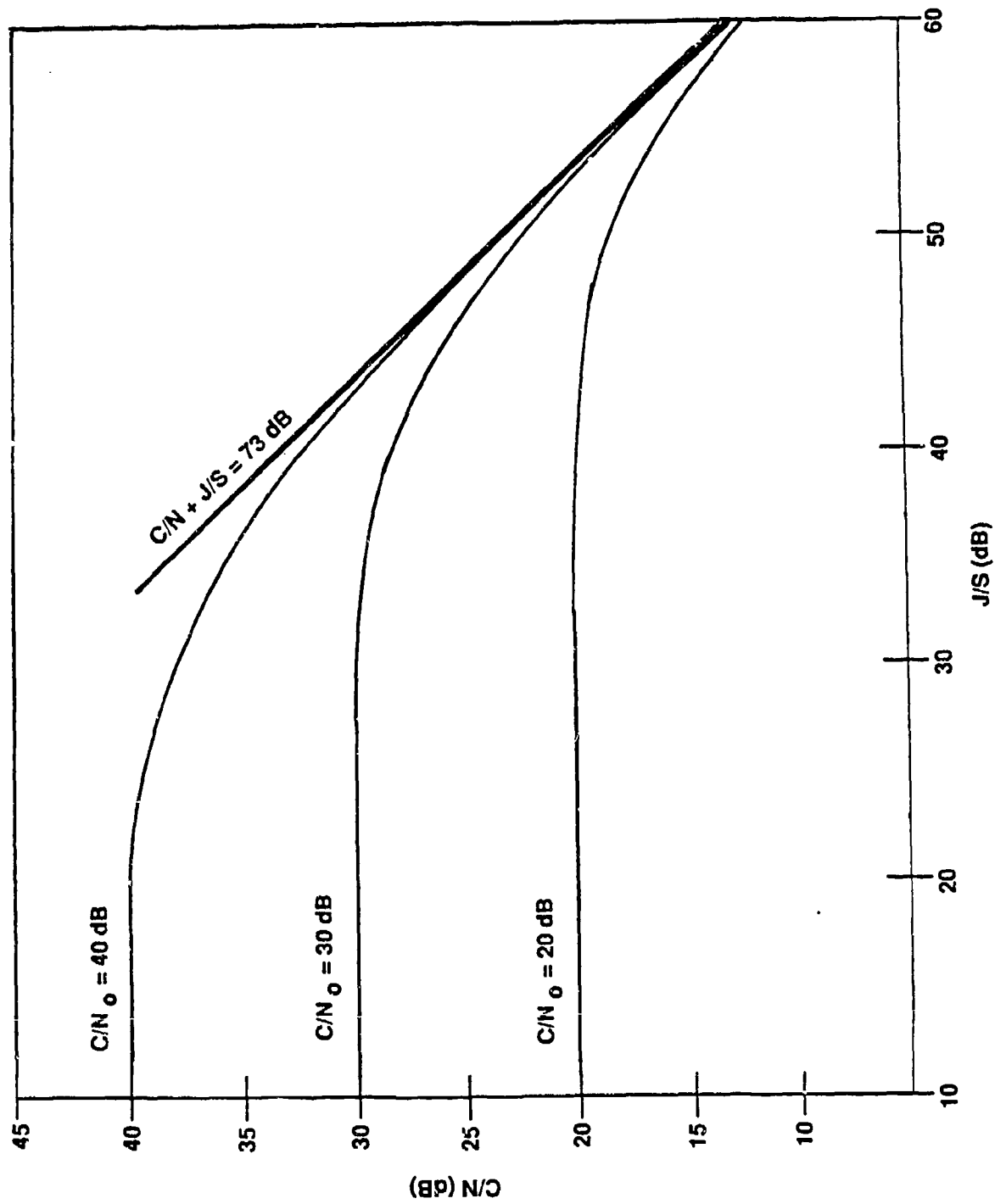


Figure 39. C/N Degradation by Noise Jamming

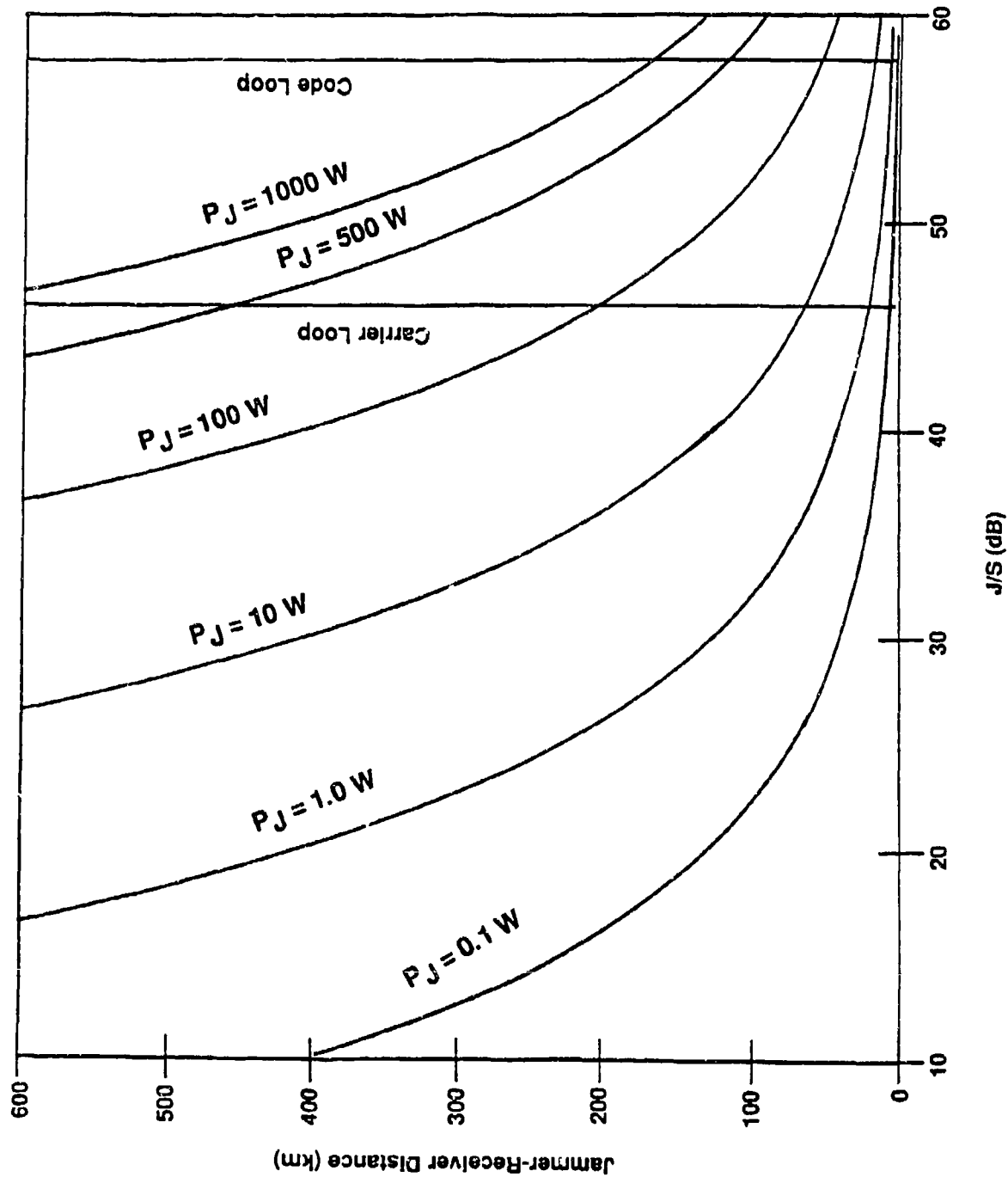


Figure 40. J/S as a Function of Jammer Power and Jammer-Receiver Distance

Finally, the data from Figure 40 are used to construct Figure 41, which shows the jammer power required, as a function of distance, to cause loss of both carrier and code loop lock. The immediate conclusion is that GPS is quite vulnerable to jamming: a 100-watt transmitter can jam carrier tracking at a range of 200 km and code tracking at a range of more than 50 km. The components for such a transmitter are readily available on the open market (almost from Radio Shack, but not quite). The antenna would be a metal rod about 5 cm long, mounted on a flat metal plate and could, if necessary, be placed on a lightweight tower to obtain line of sight to the GPS receiver. The prime power supply would have to be rated at about 400 watts and could consist of batteries for a short period of time. For battlefield jamming, a number of 5-watt jammers deployed on enemy vehicles would deny the use of GPS to ranges of 50 km or more.

There are, of course, many moves and counter-moves that can be made by the victim and the jammer in such a situation:

- The GPS receiver can use INS aiding, which will increase its loss-of-lock level by 3 to 6 dB, and will require the jammer to increase his transmitter power by a factor of 2 to 4.
- The jammer can switch from noise jamming to CW jamming. Not only is a narrow-band transmitter more efficient than a wide-band transmitter, but also the CW signal is 3 dB more effective in jamming the receiver. However, CW signals are easily removed by notch filters in the front end of the GPS receiver (a process called excision). It has been shown that up to 40 percent of the front-end bandwidth can be removed by filtering without significantly effecting the performance of the receiver.
- The jammer can use a directional antenna to increase the effective radiated power (ERP) by forming a beam in the direction of the victim receiver. A parabola about 2 meters in diameter will provide about 30 dB of gain at GPS frequencies. To counter this, the GPS receiver can use a phased-array antenna to form a null in the direction of the jammer—a null that can be automatically steered if necessary. This will be most effective if the jammer is ground based, since the GPS receiver can then limit its antenna pattern to angles well above the horizon and still see enough satellites to operate properly.
- The sequence of electronic countermeasures (ECM) and electronic counter-countermeasures (ECCM) has continued on to become EC^nM —and one is no longer sure that n is even an integer.

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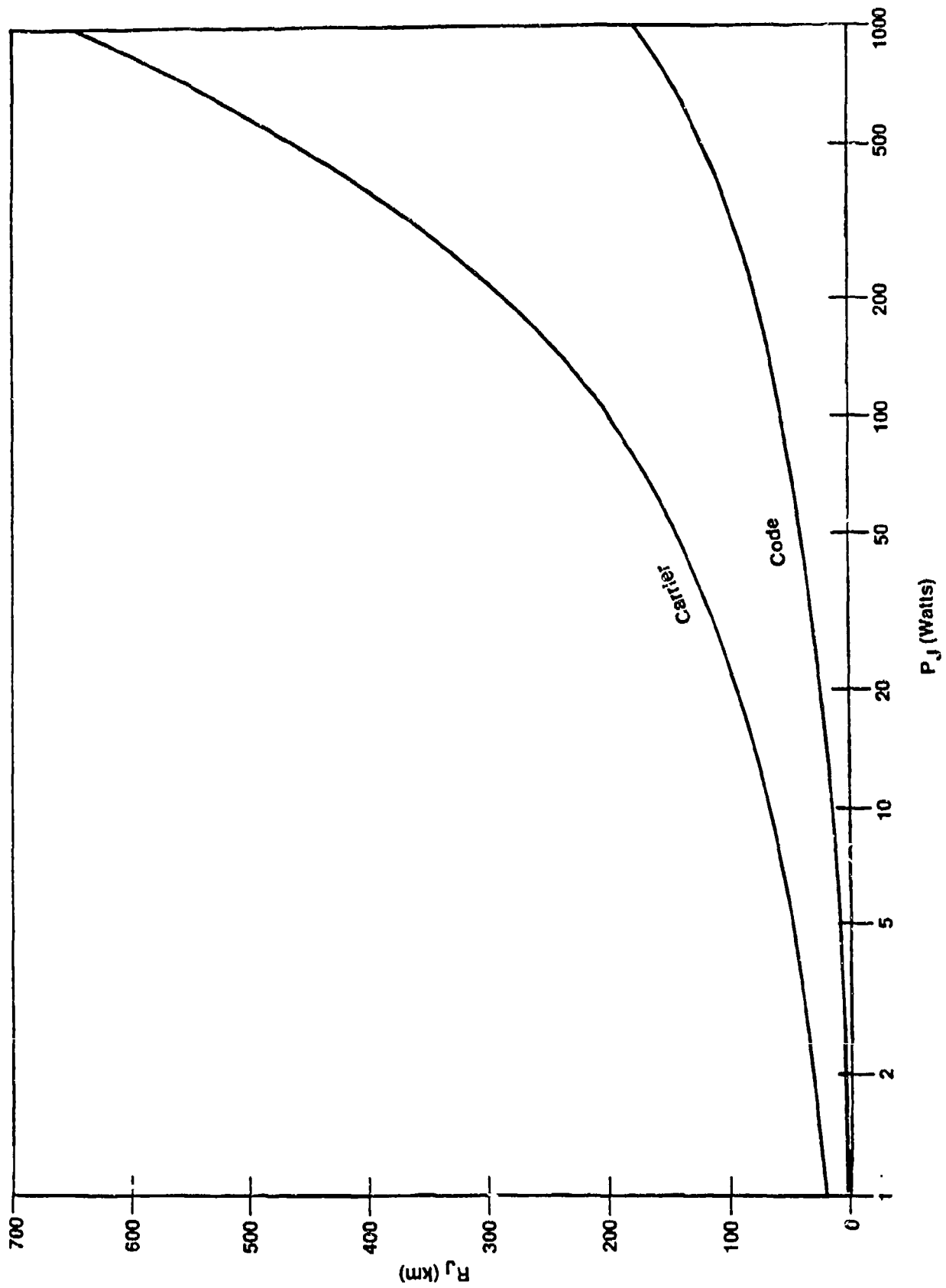


Figure 41. Jammer Power vs. Range

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The effect of jamming GPS depends, of course, on the particular application being considered. IDA Paper P-2110 (Reference VI-3) examined the case of a glide bomb which used an integrated GPS-inertial system for guidance after it was released from the delivery aircraft. Under normal conditions, using GPS position updates at one-second intervals, inertial smoothing, and Kalman filtering, the weapon would achieve an impact accuracy of about 4 meters CEP. If the GPS signal were jammed, the weapon would continue on inertial guidance alone, but the accuracy would degrade as the inertial platform drifted. Assuming that the jammer is located near the target (a reasonable assumption for a high-value target), only the last part of the trajectory would be jammed. For this case, the expected impact accuracy as a function of the length of time the GPS signal is jammed (time prior to impact) is shown in Figure 42.

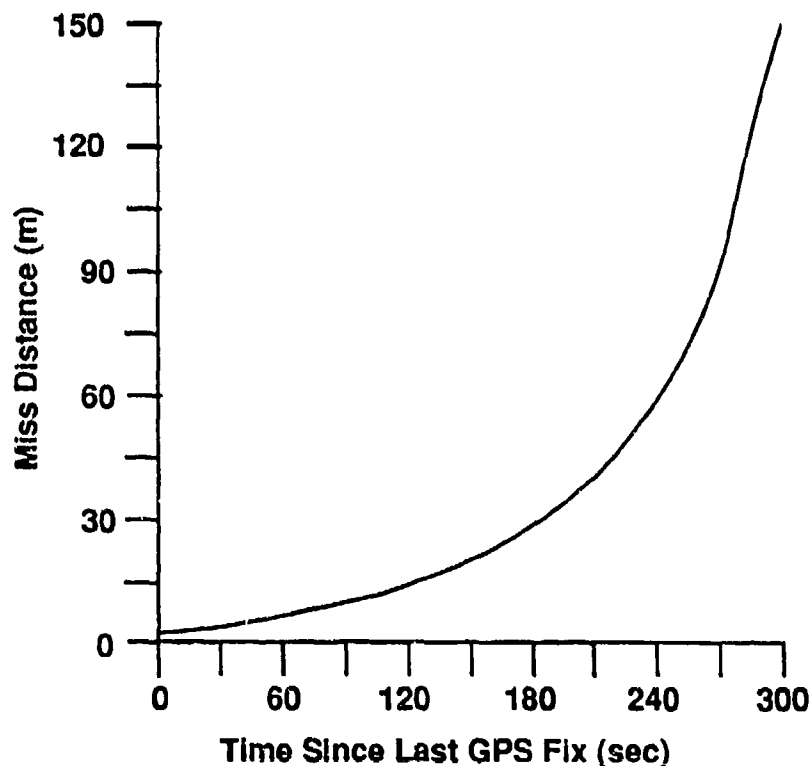


Figure 42. Effect of Jamming on Impact Accuracy

2. Loran-C Jamming

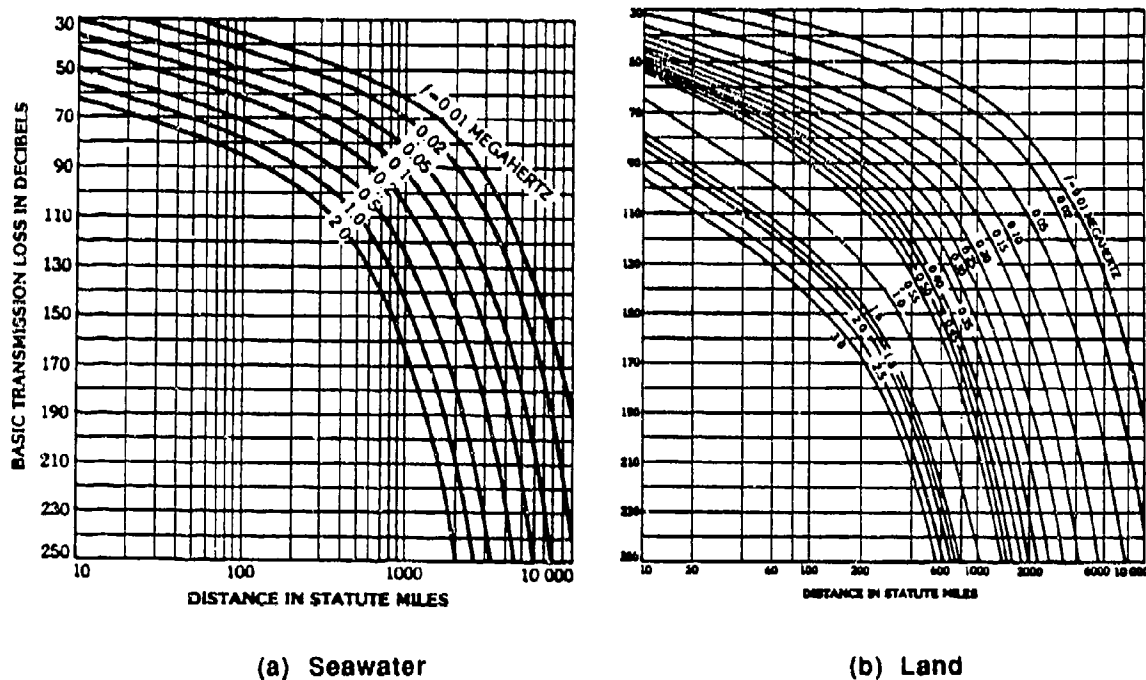
The pertinent characteristics of Loran-C are summarized below:

- Loran-C is a long-range ground-wave navigation system with an effective range of 1,000 miles or more.

- The carrier frequency is 100 kHz, and the RF bandwidth is 20 kHz.
- Loran-C transmitter sites are large fixed-plant installations. Transmitter power varies from 325 kW to 1.6 MW, depending on the site, and the antennas are top-loaded monopoles either 625 or 1,350 feet high. Even taller antennas would be desirable since they would improve the radiation efficiency (1,350 feet is less than 15 percent of the Loran wavelength), but they are not considered practical.

An analytic solution, such as was just done for GPS jamming, is not possible for Loran-C, for a variety of reasons:

- Since the Loran signal propagates along the surface of the earth, the propagation loss, which is shown in Figure 43, is greater than the free-space loss (equation VI-4) and cannot be easily calculated. Note the abrupt increase starting at a distance of about 500 miles, where the signal starts to diffract around the surface of the earth. The values in the figures are conservative since they are for a smooth spherical earth with no terrain losses.



Source: Reference VI-4

Figure 43. Basic Transmission Loss
Over a Smooth Spherical Earth

- The noise level is high and unpredictable, largely because the same conditions that allow long-range Loran propagation also transmit noise over long distances. In addition to thermal (kTB) noise (which is all that GPS sees), Loran can see another 80 dB of man-made noise and as much as 120 dB of atmospheric noise (so-called "spherics" from distant lightning strikes, for example).
- The efficiencies of the antennas at the transmitters and receivers (i.e., the ratio of the transmitter power to the radiated power in the former case) can be estimated but cannot be calculated exactly.

It is, therefore, necessary to use a graphical approach and to compare the strength of the Loran signal and the jammer signal at the receiver. Assuming that jamming is successful when these two signals are equal, we can write:

$$\frac{P_L \eta_L}{L_L} = \frac{P_J \eta_J}{L_J} \quad (\text{VI-5})$$

where: P_L, P_J = Loran and jammer transmitter powers
 η_L, η_J = Loran and jammer antenna efficiencies
 L_L, L_J = Path losses from Loran transmitter and jammer to Loran receiver

From this, the jammer power required is:

$$P_J = \left(\frac{L_J}{L_L} \right) \left(\frac{\eta_L}{\eta_J} \right) P_L \quad (\text{VI-6})$$

The analysis is then based on a few simple assumptions:

- The Loran signal and the jammer signal are equal at the receiver antenna (the basis of equations and VI-5 and VI-6).
- The Loran transmitter power is 500 kW.
- The Loran antenna is 10 times more efficient than the jammer antenna. This is probably conservative, since the jammer will not be able to erect anything like the towering guyed monopoles (with an extensive set of ground-plane radials) that are used at Loran transmitter sites.
- The Loran signal and the jammer signal both travel over the same type of terrain. This is probably not true, but no other assumption can be made unless a specific case is being considered. In any event, the path loss does not vary greatly with the type of surface: The difference in path loss between a land

path and a seawater path is seen from Figure 42 to be only about 2 dB at 100 miles and 7 dB at 1,000 miles.

With these assumptions, equation VI-6 becomes (in dB):

$$P_J = (L_J - L_L) + 67 \text{ dBW} \quad (\text{VI-7})$$

This equation is used to generate the curves in Figure 44, which shows the required jammer power as a function of the jammer-to-receiver distance, with the Loran transmitter-to-receiver distance as a parameter, for the case where both propagation paths are over land. An example will show how the curves were derived: For a receiver that is 500 miles from the Loran transmitter and 200 miles from the jammer, the propagation losses are seen from Figure 42b to be $L_L = 80 \text{ dB}$ and $L_J = 65 \text{ dB}$. Then equation VI-7 shows that the required jammer power is 52 dBW, or 160 kW.

The conclusion to be drawn from these curves is that jamming Loran requires considerable effort on the part of the enemy. For a comparison, refer back to Figure 41, which shows that a GPS receiver can be completely jammed (both code and carrier loops) by a jammer at a range of 200 miles (320 km) with a power of about 250 watts and a simple stub antenna. In the case of Loran, the distance from the Loran transmitter to the receiver must also be considered, but for the case where both the Loran transmitter and the jammer are 200 miles from the receiver, the required jammer power is seen from Figure 44 to be 67 dBW, or 5 MW. Even if the jammer moves to within 10 miles of the receiver, its power must still be 39 dBW, or 8 kW. These are not easy values to produce. The transmitters are large, heavy, and not readily available. The prime power required will be at least three times the transmitter power and the antenna, even if smaller than Loran antennas, will be a large structure. The bottom line is that, in order to jam a Loran navigation system, you need a Loran transmitter.

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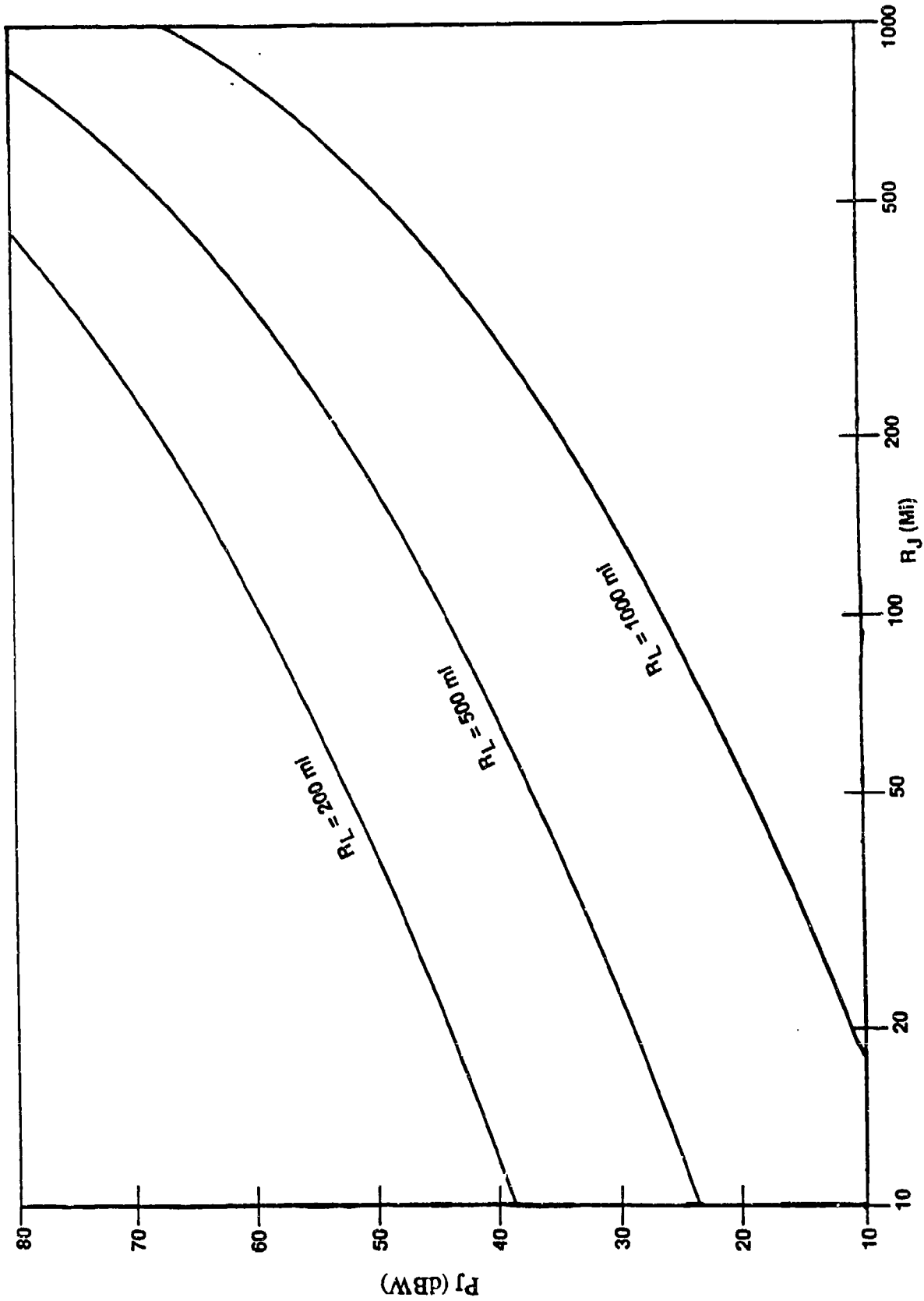


Figure 44. Jammer Power Required to Jam Loran-C

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The game of countermeasures and counter-countermeasures can again be played, but the situation is different for Loran than for GPS:

- Current Loran receivers use front-end notch filters to eliminate interfering signals. However, the Loran bandwidth is only 20 kHz. Not much filtering can be done.
- Directional antennas would be nice. A Loran station could use one to increase its signal in its coverage area, and a jammer could use one to direct its signal toward the victim receiver. However, such antenna should have to consist of arrays of monopoles, each like a Loran antenna (up to 1,350 feet tall), and this is clearly impractical. To increase signal strengths, it is easier to increase transmitter power than to increase antenna efficiency.
- Finally, a Loran jammer, like a Loran transmitter, is not easily hidden consisting, as it does, of a large transmitter, a large prime power supply, and a large antenna. It must be located within a few hundred miles of its intended victims and would surely be discovered long before it went on the air and could easily be destroyed.

On balance, Loran seems to be less vulnerable to jamming than GPS. On the other hand, the Loran stations are more vulnerable to destruction than the GPS satellites.

3. Omega Jamming

The pertinent characteristics of the Omega system are summarized below:

- Omega is an extremely long-range navigation system. Only eight stations are necessary for worldwide coverage, and around-the-world signal propagation is routine.
- Omega transmits a series of CW signals in the band from 10.2 to 13.6 kHz.
- Omega stations are large, fixed-plant installations. The antennas are mostly top-loaded monopoles up to 1,500 feet tall. The transmitter power is 150 kW but, due to the low antenna efficiency, the radiated power is only 10 kW.
- Omega signals propagate in the spherical waveguide between the earth and the ionosphere. The attenuation is very low: 2.6 dB/Mm in a north-south direction, and from 1.6 to 4.5 dB/Mm in an east-west direction (at 10.2 kHz).

Since the propagation loss (in dB) is essentially a linear function of distance (see Figures 15a and 15b), it is possible to do an analytical evaluation of Omega jamming, much as was done for GPS. However, the range of Omega is so great and the coverage area so vast that it is hard to create a realistic jamming scenario. Instead, a few general comments seem appropriate:

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- The average path length for a short-path Omega signal is probably about one-quarter of the earth's circumference (see Figure 17). For such a path, the loss would be about 30 dB if it were in a north-south direction, 20 dB if west to east, and 40 dB if east to west. The corresponding long-path losses would be 70 dB, 50 dB, and 110 dB, respectively.
- The enemy would probably choose to locate an Omega jammer on his own territory, since range is not a significant criterion, and since it would then be far easier to conceal or camouflage—an existing radiobeacon or some other tall tower could be used as the antenna, for example.

Then, depending on the directions from the Omega transmitter and the jammer to the receiver (west to east has the lowest loss) and on the distances involved, the jammer transmitter might need as much as 20 dB less or as much as 30 dB more power than the Omega transmitter in order to equal the Omega signal strength at the receiver location. Assuming equal antenna efficiencies for the jammer and the Omega station, the required jammer transmitter power would vary from 1.5 kW to 150 MW. Both are possible, but the latter is unlikely.

On the other hand, the long-path Omega signals have much higher path losses than the short-path signals. Their received levels will be 40 dB lower if both paths are north-south, and from 10 to 90 dB lower if both paths are east-west.⁹ These could be jammed with relatively modest jammer powers and antenna efficiencies. It was shown in Chapter III that many users use the long-path signals as part of their Omega navigation technique, and this would no longer be possible. However, since those users can always revert to hyperbolic or range-range navigation using only short-path signals, this must be regarded as more of an inconvenience than a loss of services.

No significant ECM/ECCM techniques are possible with Omega:

- Notch filters cannot be used since Omega is a CW system. The jamming signal must have the same frequency as the Omega signal in order to be effective.
- Directional antennas are clearly impractical since the dimensions of an effective array must be an appreciable fraction of a wavelength, and Omega wavelengths are 20 to 30 km.

Finally, it should be noted that Omega was designed to be a worldwide long-range system. It is well suited for en route transoceanic navigation where its accuracy of 2-4 nmi

⁹ Remember that an east to west short path corresponds to a west to east long path, and vice versa.

is more than adequate but, even in its differential mode (accuracy 0.25-0.5 nmi), it is not suitable for precision navigation or weapons delivery and could hardly be regarded as a strategic or tactical threat. Thus, although a determined enemy could interfere with or even deny the use of some areas of Omega coverage, it seems unlikely that he would try.

C. CONCLUSIONS

If technical performance were the only criterion, GPS would clearly be the navigation system of choice since it provides worldwide capability to measure both position and velocity in three dimensions with an accuracy unequaled by any of the other systems.

In many respects, Transit would be the second choice. Its accuracy is nearly equal to that of GPS,¹⁰ and its satellite is considerably simpler and cheaper: For one thing, using the Doppler shift rather than time and/or frequency as the measured parameter obviates the need for precision atomic clocks. The major design flaw of Transit is that all the satellites use the same carrier frequencies and the same modulation format, so the system can only have one satellite in view at a time. Therefore, it is limited to two-dimensional fixes, to position measurements only, and to a minimum delay of 30 minutes between fixes and is not suitable for guidance of aircraft or missiles. If the satellites had separate frequencies (like GLONASS) or separate identifying codes (like GPS), it would be possible to have several in view simultaneously, and continuous 3D fixes would be possible.¹¹ Unfortunately for Transit, GPS already does this, and it is not possible to justify two separate satellite systems. Transit, therefore, will be phased out in 1996.

As far as the other systems are concerned, several points should be considered:

- Loran and Omega were designed to be long-range navigation systems, and they are more than satisfactory for this purpose.
- Loran and Omega both penetrate sea water to some extent and can be received by submerged submarines.
- In its differential mode, Loran has an accuracy of 10-20 meters and can be used for both precision navigation and weapons delivery.

Finally, the discussion earlier in this chapter showed that GPS, despite its prodigious processing gain, can be jammed by small, inexpensive transmitters assembled

¹⁰ However, Transit measures only position, only in two dimensions, and only if the velocity of the platform is accurately known.

¹¹ The jammer resistance of Transit was not discussed because the system is to be phased out, but it will be similar to that of GPS.

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from readily available components. Loran and Omega jamming requires large, fixed-plant installations and a significantly larger expenditure of time and effort on the part of the enemy ("To jam Loran, one needs a Loran transmitter").

Data showing the current and projected number of users of each of the four major Worldwide Radionavigation Systems have been extracted from the latest edition of the Federal Radionavigation Plan [Reference VI-2] and are summarized in Table 19.

Table 19. Radionavigation System Users

System	Total Users				Termination Data
	1993	1996	2000	2005	
Transit	85,000	70,000	-	-	1996
Omega	27,425	18,100	7,140	2,115	2005
Loran-C	687,050	818,600	866,500	804,000	None
GPS	40,700	105,000	417,000	3,218,000	None

The following observations can be made:

- The Transit system, which has been superseded by GPS, will be terminated in 1996.
- The number of Omega users will decrease steadily, and the system will be terminated in 2005.
- The number of Loran-C users is projected to increase through 1996 and to then decrease only slightly through 2005. There are no current plans to terminate the system, but the situation will be reviewed again in 1996.
- GPS will continue to grow for the foreseeable future and will become the primary navigation system for both civilian and military applications.

There can be no real argument against these projections and recommendations, at least on the purely technical grounds of accuracy, availability, and reliability. The only cautionary note would be that GPS is vulnerable to jamming and other interference and that an alternative radionavigation system should be retained for fallback use.

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**APPENDIX A
GLOSSARY**

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GLOSSARY

bps	bits per second
C/A	clear/acquisition code
C/N	carrier-to-noise ratio
CDMA	code division multiple access
C _{cc}	centicycle
CEP	circular error probable
cm	centimeter
CRT	cathode ray tube
CW	continuous wave
Cytac	cycle-matching tactical bombing system
dB	decibel
DMA	Defense Mapping Agency
drms	distance root mean squared
ECCM	electronic counter-countermeasure
ECU	electronic countermeasure
ERP	effective radiated power
FDMA	frequency division multiple access
GDOP	Geometric Dilution of Precision
GMT	Greenwich Mean Time
GPS	Global Positioning System
GRI	Group Repetition Interval
HF	high frequency
HOW	handover word
Hz	hertz
ILS	Instrument Landing System
IMU	Inertial Measurement Unit
INS	inertial navigation system

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J/S	jammer-to-signal ratio
JTIDS	Joint Tactical Information Distribution System
kHz	kilohertz
km	kilometer
kW	kilowatt
LF	low frequency
LORAN	long-range navigation
Mbps	megabits per second
MF	medium frequency
MHz	megahertz
MIT	Massachusetts Institute of Technology
MLS	microwave landing system
Mm	megameter
ms	millisecond
mW	milliwatt
nmi	nautical mile
ns	nanosecond
NTS	Navigation Technology Satellite
P	precision code
PCA	Polar Cap Anomaly
PLRS	Position Location Reporting System
PN	pseudonoise
PPC	Propagation Correction
pps	pulse per second
RF	radio frequency
rms	root mean square
rss	root sum square
S/N	signal-to-noise (ratio)
SA	Selective Availability
SAM	System Area Monitor
SID	Sudden Ionospheric Disturbance

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SPS	Standard Positioning Service
TD	time difference
TLM	telemetry
UTC	Coordinated Universal Time
UTM	Universal Transverse Mercator
VHF	very high frequency
VLF	very low frequency
VOR	very high frequency omnidirectional range
μ s	microsecond

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